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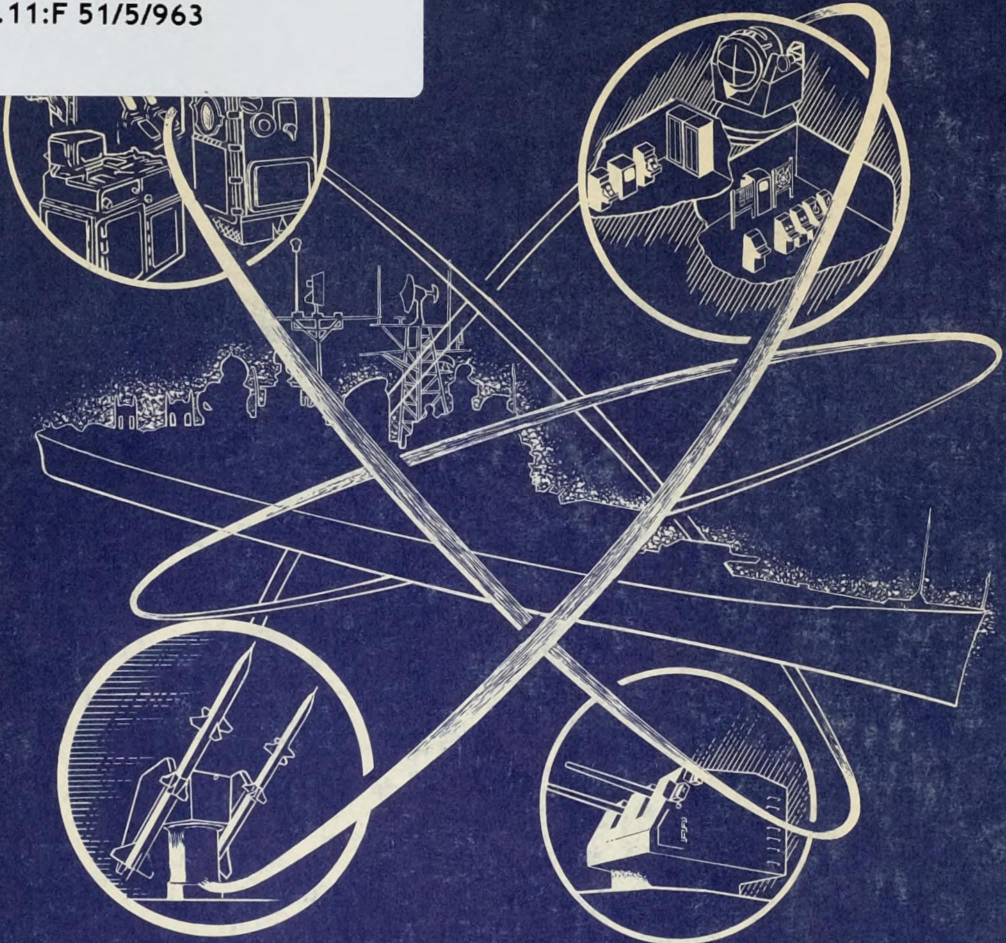

FIRE CONTROL TECHNICIAN 2

BUREAU OF NAVAL PERSONNEL

NAVY TRAINING COURSE NAVPERS 10174-A

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PREFACE

This Navy Training Course was written to serve as an aid for enlisted men of the U.S. Navy and Naval Reserve who are preparing for advancement to the rates of Fire Control Technician G (gun fire control) 2 and Fire Control Technician M (missile fire control) 2. It is one of a series of Navy Training Courses designed to give enlisted men background information necessary for the proper performance of the duties of their rate.

The predominant factor in the selection of content for this publication has been the Manual of Qualifications for Advancement in Rating, NavPers 18068-A, the 1963 revision (see Appendix II), as it relates to FTG2 and FTM2, because it was found advisable to keep the study material in one volume.

This book was prepared by the U. S. Navy Training Publications Center for the Bureau of Naval Personnel. Special credit is given to the Bureau of Naval Weapons and to the Fire Control Technician School, Class B, Great Lakes, Illinois, for assisting in the technical review of the text. Acknowledgement is made to the Mobile Ordnance Service Division of the U. S. Naval Station, Navy Yard Annex, Washington, D. C., whose comments and suggestion have been most helpful.

CREDITS

SOURCE	FIGURE
McGraw-Hill Book Co. Inc.	6-11

1963 Edition

THE UNITED STATES NAVY

GUARDIAN OF OUR COUNTRY

The United States Navy is responsible for maintaining control of the sea and is a ready force on watch at home and overseas, capable of strong action to preserve the peace or of instant offensive action to win in war.

It is upon the maintenance of this control that our country's glorious future depends; the United States Navy exists to make it so.

WE SERVE WITH HONOR

Tradition, valor, and victory are the Navy's heritage from the past. To these may be added dedication, discipline, and vigilance as the watchwords of the present and the future.

At home or on distant stations we serve with pride, confident in the respect of our country, our shipmates, and our families.

Our responsibilities sober us; our adversities strengthen us.

Service to God and Country is our special privilege. We serve with honor.

THE FUTURE OF THE NAVY

The Navy will always employ new weapons, new techniques, and greater power to protect and defend the United States on the sea, under the sea, and in the air.

Now and in the future, control of the sea gives the United States her greatest advantage for the maintenance of peace and for victory in war.

Mobility, surprise, dispersal, and offensive power are the keynotes of the new Navy. The roots of the Navy lie in a strong belief in the future, in continued dedication to our tasks, and in reflection on our heritage from the past.

Never have our opportunities and our responsibilities been greater.

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READING LIST

NAVY TRAINING COURSES

Mathematics, Volume 1, NavPers 10069-B

Basic Electricity (less chs. 2, 12, & 15), NavPers 10086-A

Basic Electronics, NavPers 10087-A

Fire Control Fundamentals, NavPers 91900

Fire Control Radar Fundamentals, NavPers 91901

Fire Control Radar Special Circuits, NavPers 92213

OTHER PUBLICATIONS

Weapons Systems Fundamentals, Volume 1, OP 3000

Lubrication of Ordnance Equipment, OD 3000

United States Navy Safety Precautions, OPNAV 34P1

USAFI COURSES

United States Armed Forces Institute (USAFI) courses for additional reading and study are available through your Information and Education Officer.* A partial list of those courses applicable to your rate follows:

Number	Title
C 151	General Mathematics I
C 152	General Mathematics II
C 781	Fundamentals of Electricity

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*"Members of the United States Armed Forces Reserve components, when on active duty, are eligible to enroll for USAFI courses, services, and materials if the orders calling them to active duty specify a period of 120 days or more, or if they have been on active duty for a period of 120 days or more, regardless of the time specified in the active duty orders."

CHAPTER 1

GUIDE TO ADVANCEMENT

This training course is designed to help you meet the professional (technical) qualifications for advancement to Fire Control Technician 2. The Fire Control Technician qualifications which were used as a guide in the preparation of this training course were current through the June 1963 revision of the Quals Manual, NavPers 18068-A. Therefore, changes in the qualifications occurring after the June 1963 revision, are not reflected in the information given here.

This book is organized to give you a systematic understanding of your job. Chapters 2 and 3 cover servo devices and servosystems. Chapter 4 discusses the amplidyne control circuits of Gun Director Mk 37, showing an application of the fundamentals contained in the preceding chapters. Chapters 5 and 6 take up fire control radars and their maintenance. The fire control problem, both surface and air, for gun and missile is explained in chapters 7 through 11. Chapter 12 introduces you to the submarine torpedo fire control problem. Chapter 13 introduces the stereoscopic rangefinder, and covers the necessary correction for ranging. General maintenance and troubleshooting techniques are discussed in chapter 14.

The remainder of this chapter gives information on the enlisted rating structure, the Fire Control Technician rating, requirements and procedures for advancement in rating, and references that will help you in working for advancement and in performing your duties as a technician. This chapter includes information on how to use Navy Training Courses. Therefore, it is strongly recommended that you study this chapter carefully before beginning intensive study of the remainder of this training course.

THE ENLISTED RATING STRUCTURE

The present elisted rating structure, established in 1957, includes three types of ratings—general ratings, service ratings, and emergency ratings.

GENERAL RATINGS identify broad occupational fields of related duties and functions. Some general ratings include service ratings; others do not. Both Regular Navy and Naval Reserve personnel may hold general ratings.

SERVICE RATINGS identify subdivisions or specialities within a general rating. Although service ratings can exist at any petty officer level, they are most common at the PO3 and PO2 levels. Both Regular Navy and Naval Reserve personnel may hold service ratings.

EMERGENCY RATINGS generally identify civilian occupational fields. Emergency ratings do not need to be identified as ratings in the peacetime Navy, but their identification is required in time of war.

THE FIRE CONTROL TECHNICIAN RATING

In the FT 3 Navy Training Course you were introduced to the elements of the fire control problem, and to the theory behind the equipment necessary to solve the problem. The FT 3 course furnishes the foundation for understanding the material covered in this course. The FT 2 course continues to expand your knowledge of theory, but there is more emphasis on working knowledge.

All Navy ships, except a few auxiliary ships, have fire control equipment installed. Thus you may spend the seagoing portion of your career aboard almost any type of Navy ship. You may be one of a few FTs aboard a destroyer, or one of many aboard a carrier. As an FT 2 your billet will probably require you to maintain an entire fire control system or station with only limited supervision.

The increased performance required of fire control equipment in both capability and accuracy tend to increase their complexity and reduce their allowable tolerances. The margin for error has become razoredge thin. Thus the maintenance of fire control equipment demands technical competence and diligence. The degree of your responsibility and the complexity of maintenance assigned to you, will depend solely on you.

Besides the occupational or professional duties, you have military dutes. This course is concerned with your professional duties—NOT your military duties.

KINDS OF RATING

Earlier we defined the three types of ratings that are included in the enlisted rating structure. The rating structure of the Fire Control Technician rating includes only two of the types mentioned. There are:

1. a general rating at pay grades E-7 through E-9.
2. two service ratings—FTM (Missile Fire Control) and FTG (Gun Fire Control) in pay grades E-4 through E-6.

As you can see, there are no emergency ratings for FTs.

YOUR PART IN NAVAL LEADERSHIP

In 1953 the Navy and Marine Corps placed in effect a program of Moral Leadership and Character Education to ensure that naval leadership remains at a consistently high level. In 1958 the Secretary of the Navy issued General Order 21. The objective of this general order is to revitalize and reemphasize naval leadership in all its aspects. The three major aspects of naval leadership are:

1. Technical competence
2. Inspirational
3. Moral

As a Fire Control Technician you have an important practical part to play in your shipboard leadership program. You have charge of a group of men. This puts you in a position of leadership. You have two responsibilities—to accomplish a mission and to take care of your men. The general principles and techniques of leadership are fully discussed in Military Requirements for PO 3 & 2, NavPers 10056-A. However, let's do a little thinking about how you can help to carry out General Order 21 on a day-to-day basis.

Assume for a moment that your mission aboard ship is to maintain a fire control system, and you have men to assist you. Now a big part of your job is to learn everything you can about the system, and to pass on your knowledge to your men. Technical competence is a major aspect of good leadership. But being a skilled technician is not enough. You must inspire your men to do their work as efficiently as possible.

A national characteristic of the American fighting man is that he wants to know why he is called upon to perform certain tasks. You must explain to your men the importance of their work and how it affects the overall fighting efficiency of your ship. During gunnery exercises or drills make them feel they are winning a war, not just turning knobs on equipment. Keep in mind they are the men who will fight by your side in combat. When led with courage, spirit, and intelligence, they will fight as willingly and as efficiently as any fighter in the world. But it is up to you to provide inspiration.

To inspire your men and others, you must have a strong moral character. Some of the character traits you can develop by conscientious study and practice are loyalty, integrity, and quiet self-confidence.

Loyalty is one of the most essential factors of leadership. Experienced officers and petty officers say that they would rather have a loyal man who is not an excellent worker than a disloyal man who does excellent work. Loyalty to the country, to the Navy, to your ship, to your division, to your chief, to your senior petty officer, and to the men who work with and for you—these are prime requisites of leadership. The surest way to get the respect and loyalty of your men is to be loyal to yourself.

Everytime you feel the urge to criticize the handling of your ship's affairs, stop short! You are part, and an important part, of your ship. How can you expect your men to be loyal if you are not?

Deal with your men squarely and honestly. If you do, you will win and hold their respect. Be dependable. This mark of integrity involves keeping promises. A reputation of being a "square shooter" is worth every effort on your part. Help to build this reputation early by not tolerating "gun-decking" or other methods of falsifying reports.

Good leaders have a quiet self-confidence (not an arrogant or cocky manner) based on thorough knowledge of the job and in a belief in their own ability. Confidence begets confidence. If you have confidence in yourself, you can inspire confidence in your men.

ADVANCEMENT IN RATING

Some of the rewards of advancement in rating are easy to see. You get more pay. Your job assignments become more interesting and more challenging. You are regarded with greater respect by officers and enlisted personnel. You enjoy the satisfaction of getting ahead in your chosen Navy career.

But the advantages of advancing in rating are not yours alone. The Navy also profits. Highly trained personnel are essential to the functioning of the Navy. By each advancement in rating, you increase your value to the Navy in two ways. First, you become more valuable as a technical specialist in your own rating. And second, you become more valuable as a person who can train others and thus make far-reaching contributions to the entire Navy.

HOW TO QUALIFY FOR ADVANCEMENT

What must you do to qualify for advancement in rating? The requirements may change from time to time, but usually you must:

1. Have a certain amount of time in your present grade.
2. Complete the required military and professional training courses.
3. Demonstrate your ability to perform all the PRACTICAL requirements for advancement by completing the Record of Practical Factors, NavPers 760.
4. Be recommended by your commanding officer, after the petty officers and officers supervising your work have indicated that they consider you capable of performing the duties of the next higher rate.
5. Demonstrate your KNOWLEDGE by passing a written examination on (a) military requirements and (b) professional qualifications.

Some of these general requirements may be modified in certain ways. Figure 1-1 gives a more detailed view of the requirements for advancement of active duty personnel; figure 1-2 gives this information for inactive duty personnel.

Remember that the requirements for advancement can change. Check with your information and education officer to be sure that you know the most recent requirements.

Advancement in rating is not automatic. After you have met all the requirements, you are ELIGIBLE for advancement. You will actually be advanced in rating only if you meet all the requirements (including making a high enough score on the written examination) and if the quotas for your rating permit your advancement.

HOW TO PREPARE FOR ADVANCEMENT

What must you do to prepare for advancement in rating? You must study the qualifications for advancement, work on the practical factors, study the required Navy Training Courses, and study other material that is required for advancement in your rating. To prepare for advancement, you will need to be familiar with (1) the Quals Manual, (2) the Record of Practical Factors, NavPers 760, (3) a NavPers publication called Training Publications for Advancement in Rating, NavPers 10052, and (4) applicable Navy Training Courses. Figure 1-3 illustrates these materials; the following sections describe them and give you some practical suggestions on how to use them in preparing for advancement.

The Quals Manual

The Manual of Qualifications for Advancement in Rating, NavPers 18068-A, 1963 revision, gives the minimum requirements for advancement to each rate within each rating. This manual is usually called the "Quals Manual," and the qualifications themselves are often called "quals." The qualifications are of two general types: (1) military requirements, and (2) professional or technical qualifications.

MILITARY REQUIREMENTS apply to all ratings rather than to any one particular rating. Military requirements for advancement to third class and second class petty officer rates deal with military conduct, naval organization, military justice, security, watch standing, and other subjects which are required of petty officers in all ratings.

PROFESSIONAL QUALIFICATIONS are technical or professional requirements that are directly related to the work of each rating.

Both the military requirements and the professional qualifications are divided into subject matter groups; then, within each subject matter group, they are divided into PRACTICAL FACTORS and KNOWLEDGE FACTORS. Practical factors are things you must be able to DO. Knowledge factors are things you must KNOW in order to perform the duties of your rating.

The professional qualifications for advancement in your rating are printed as an appendix at the back of this training course. Study these qualifications and the military requirements carefully. The written examination for advancement in rating will contain questions relating to the practical factors and the knowledge factors

ACTIVE DUTY ADVANCEMENT REQUIREMENTS

REQUIREMENTS *	E1 to E2	E2 to E3	E3 to E4	E4 to E5	E5 to E6	E6 to E7	† E7 to E8	‡ E8 to E9
SERVICE	4 mos. service—or completion of recruit training.	6 mos. as E-2.	6 mos. as E-3.	12 mos. as E-4.	24 mos. as E-5.	36 mos. as E-6.	48 mos. as E-7. 8 of 11 years total service must be enlisted. Must be permanent appointment.	24 mos. as E-8. 10 of 13 years total service must be enlisted.
SCHOOL	Recruit Training.		Class A for PR3, DT3, PT3. ǂAME 3			Class B for AGCA, MUCA, MNCA.		
PRACTICAL FACTORS	Locally prepared check-offs.	Records of Practical Factors, NavPers 760, must be completed for E-3 and all PO advancements.						
PERFORMANCE TEST			Specified ratings must complete applicable performance tests before taking examinations.					
ENLISTED PERFORMANCE EVALUATION	As used by CO when approving advancement.		Counts toward performance factor credit in advancement multiple.					
EXAMINATIONS	Locally prepared tests.		Service-wide examinations required for all PO advancements.				Service-wide, selection board, and physical.	
NAVY TRAINING COURSE (INCLUDING MILITARY REQUIREMENTS)		Required for E-3 and all PO advancements unless waived because of school completion, but need not be repeated if identical course has already been completed. See NavPers 10052 (current edition).					Correspondence courses and recommended reading. See NavPers 10052 (current edition).	
AUTHORIZATION	Commanding Officer		U.S. Naval Examining Center			Bureau of Naval Personnel		
	TARS are advanced to fill vacancies and must be approved by CNARESTRA.							

* All advancements require commanding officer's recommendation.
† 2 years obligated service required.
‡ 3 years obligated service required.
ǂEffective 1 Jan. 1963.

Figure 1-1.—Active duty advancement requirements.

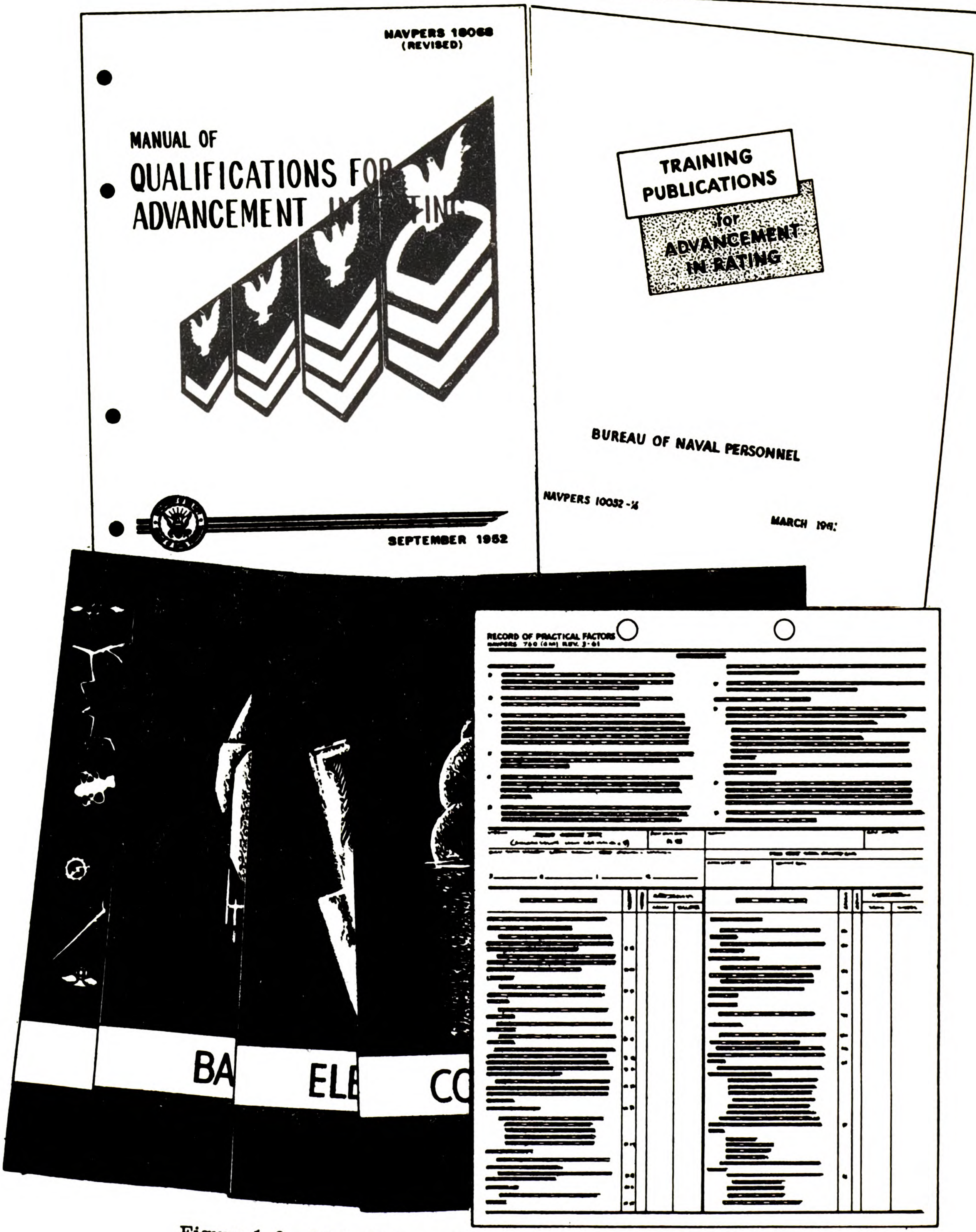
INACTIVE DUTY ADVANCEMENT REQUIREMENTS

REQUIREMENTS *		E1 to E2	E2 to E3	E3 to E4	E4 to E5	E5 to E6	E6 to E7	E8	E9
	FOR THESE DRILLS PER YEAR								
TOTAL TIME IN GRADE	48	6 mos.	6 mos.	15 mos.	18 mos.	24 mos.	36 mos.	48 mos.	24 mos.
	24	9 mos.	9 mos.	15 mos.	18 mos.	24 mos.	36 mos.	48 mos.	24 mos.
	NON-DRILLING	12 mos.	24 mos.	24 mos.	36 mos.	48 mos.	48 mos.		
DRILLS ATTENDED IN GRADE †	48	18	18	45	54	72	108	144	72
	24	16	16	27	32	42	64	85	32
TOTAL TRAINING DUTY IN GRADE †	48	14 days	14 days	14 days	14 days	28 days	42 days	56 days	28 days
	24	14 days	14 days	14 days	14 days	28 days	42 days	56 days	28 days
	NON-DRILLING	None	None	14 days	14 days	28 days	28 days		
PERFORMANCE TESTS				Specified ratings must complete applicable performance tests before taking examination.					
PRACTICAL FACTORS (INCLUDING MILITARY REQUIREMENTS)		Record of Practical Factors, NavPers 760, must be completed for all advancements.							
NAVY TRAINING COURSE (INCLUDING MILITARY REQUIREMENTS)		Completion of applicable course or courses must be entered in service record.							
EXAMINATION		Standard exams are used where available, otherwise locally prepared exams are used.						Standard EXAM, Selection Board, and Physical.	
AUTHORIZATION		District commandant or CNARESTRA					Bureau of Naval Personnel		

* Recommendation by commanding officer required for all advancements.

† Active duty periods may be substituted for drills and training duty.

Figure 1-2.—Inactive duty advancement requirements.


NAVPERS 18068
(REVISED)

MANUAL OF
QUALIFICATIONS FOR
ADVANCEMENT IN RATING

SEPTEMBER 1952

TRAINING
PUBLICATIONS
for
ADVANCEMENT
IN RATING

BUREAU OF NAVAL PERSONNEL

NAVPERS 10052-H

MARCH 1961

RECORD OF PRACTICAL FACTORS
NAVPERS 760 (OM) REV. 3-61

Figure 1-3.—Materials used in preparing for advancement.

of both the military requirements and the professional qualifications. If you are working for advancement to second class, remember that you may be examined on third class qualifications as well as on second class qualifications.

The Quals Manual is kept current by means of changes. The professional qualifications for your rating which are printed as an appendix to this training course were current at the time the course was printed. By the time you are studying this course, however, the quals for your rating may have been changed. Be sure you have checked with an UP-TO-DATE copy of the Quals Manual.

Record of Practical Factors

Before you can take the servicewide examination for advancement in rating, there must be an entry in your service record to show that you have qualified in the practical factors of both the military requirements and the professional qualifications. A special form known as the RECORD OF PRACTICAL FACTORS, NavPers 760, is used to keep a record of your practical factor qualifications. This form is available for each rating. The form lists all practical factors, both military and professional. As you demonstrate your ability to perform each practical factor, appropriate entries are made in the DATE and INITIALS columns.

Changes are made periodically to the Manual of Qualifications for Advancement in Rating, and revised forms of NavPers 760 are provided when necessary. Extra space is allowed on the Record of Practical Factors for entering additional practical factors as they are published in changes to the Quals Manual. The Record of Practical Factors also provides space for recording demonstrated proficiency in skills which are within the general scope of the rating but which are not identified as minimum qualifications for advancement.

If you are transferred before you qualify in all practical factors, the NavPers 760 form should be forwarded with your service record to your next duty station. You can save yourself a lot of trouble by making sure that this form is actually inserted in your service record before you are transferred. If the form is not in your service record, you may be required to start all over again and requalify in the practical factors which have already been checked off.

NavPers 10052

Training Publications for Advancement in Rating, NavPers 10052 (revised), is a very important publication for anyone preparing for advancement in rating. This bibliography lists required and recommended Navy Training Courses and other reference material to be used by personnel working for advancement in rating. NavPers 10052 is revised and issued once each year by the Bureau of Naval Personnel. Each revised edition is identified by a letter following the NavPers number. When using this publication, be SURE that you have the most recent edition.

If extensive changes in qualifications occur in any rating between the annual revisions of NavPers 10052, a supplementary list of study material may be issued in the form of a BuPers Notice. When you are prearing for advancement, check to see whether changes have been made in the qualifications for your rating. If changes have been made, see if a BuPers Notice has been issued to supplement NavPers 10052 for your rating.

The required and recommended references are listed by rate level in NavPers 10052. If you are working for advancement to third class, study the material that is listed for third class. If you are working for advancement to second class, study the material that is listed for second class; but remember that you are also responsible for the references listed at the third class level.

In using NavPers 10052, you will notice that some Navy Training Courses are marked with an asterisk (*). Any course marked in this way is MANDATORY—that is, it must be completed at the indicated rate level before you can be eligible to take the servicewide examination for advancement in rating. Each mandatory course may be completed by (1) passing the appropriate enlisted correspondence course that is based on the mandatory training course; (2) passing locally prepared tests based on the information given in the training course; or (3) in some cases, successfully completing an appropriate Class A school.

Do not overlook the section of NavPers 10052 which lists the required and recommended references relating to the military requirements for advancement. Personnel of ALL ratings must complete the mandatory military requirements training course for the appropriate rate level before they can be eligible to advance in rating.

The references in NavPers 10052 which are recommended but not mandatory should also be studied carefully. ALL references listed in NavPers 10052 may be used as source material for the written examinations, at the appropriate rate levels.

Navy Training Courses

There are two general types of Navy Training Courses. RATING COURSES (such as this one) are prepared for most enlisted ratings. A rating training course gives information that is directly related to the professional qualifications of ONE rating. SUBJECT MATTER COURSES or BASIC COURSES give information that applies to more than one rating.

Navy Training Courses are revised from time to time to keep them up to date technically. The revision of a Navy Training Course is identified by a letter following the NavPers number. You can tell whether any particular copy of a Navy Training Course is the latest edition by checking the NavPers number and the letter following this number in the most recent edition of List of Training Manuals and Correspondence Courses, NavPers 10061. (NavPers 10061 is actually a catalog that lists all current training courses and correspondence courses; you will find this catalog useful in planning your study program.)

Navy Training Courses are designed to help you prepare for advancement in rating. The following suggestions may help you to make the best use of this course and other Navy training publications when you are preparing for advancement in rating.

1. Study the military requirements and the professional qualifications for your rating before you study the training course, and refer to the quals frequently as you study. Remember, you are studying the training course primarily in order to meet these quals.

2. Set up a regular study plan. It will probably be easier for you to stick to a schedule if you can plan to study at the same time each day. If possible, schedule your studying for a time of day when you will not have too many interruptions or distractions.

3. Before you begin to study any part of the training course intensively, become familiar with the entire book. Read the preface and the table of contents. Check through the index. Look at the appendixes. Thumb through the book without any particular plan, looking at the illustrations and reading bits here and there are you see things that interest you.

4. Look at the training course in more detail, to see how it is organized. Look at the table of contents again. Then, chapter by chapter, read the introduction, the headings, and the subheadings. This will give you a pretty clear picture of the scope and content of the book. As you look through the book in this way, ask yourself some questions: What do I need to learn about this? What do I already know about this? How is this information related to information given in other chapters? How is this information related to the qualifications for advancement in rating?

5. When you have a general idea of what is in the training course and how it is organized, fill in the details by intensive study. In each study period, try to cover a complete unit—it may be a chapter, a section of a chapter, or a chapter, or a subsection. The amount of material that you can cover at one time will vary. If you know the subject well, or if the material is easy, you can cover quite a lot at one time. Difficult or unfamiliar material will require more study time.

6. In studying any one unit—chapter, section, or subsection—write down the questions that occur to you. Many people find it helpful to make a written outline of the unit as they study, or at least to write down the most important ideas.

7. As you study, relate the information in the training course to the knowledge you already have. When you read about a process, a skill, or a situation, try to see how this information ties in with your own past experience.

8. When you have finished studying a unit, take time out to see what you have learned. Look back over your notes and questions. Maybe some of your questions have been answered, but perhaps you still have some that are not answered. Without looking at the training course, write down the main ideas that you have gotten from studying this unit. Don't just quote the book. If you can't give these ideas in your own words, the chances are that you have not really mastered the information.

9. Use Enlisted Correspondence Courses whenever you can. The correspondence courses are based on Navy Training Courses or on other appropriate texts. As mentioned before, completion of a mandatory Navy Training Course

can be accomplished by passing an Enlisted Correspondence Course based on the Navy Training Course. You will probably find it helpful to take other correspondence courses, as well as those based on mandatory training courses. Taking a correspondence course helps you to master the information given in the training course, and also helps you see how much you have learned.

10. Think of your future as you study Navy Training Courses. You are working for advancement to third class or second class right now, but someday you will be working toward higher rates. Anything extra that you can learn now will help you both now and later.

SOURCES OR INFORMATION

One of the most useful things you can learn about a subject is how to find out more about it. No single publication can give you all the information you need to perform the duties of your rating. You should learn where to look for accurate, authoritative, up-to-date information on all subjects related to the military requirements for advancement and the professional qualifications of your rating.

Some of the publications described here are subject to change or revision from time to time—some at regular intervals, others as the need arises. When using any publication that is subject to change or revision, be sure that you have the latest edition. When using any publication that is kept current by means of changes, be sure you have a copy in which all official changes have been made. Studying canceled or obsolete information will not help you to do your work or to advance in rating; it is likely to be a waste of time, and may even be seriously misleading.

OTHER SOURCES

Ordnance Pamphlets (OPs) are books issued by the Bureau of Naval Weapons (BuWeps). Ordnance pamphlets contain detailed information on the description and maintenance of each unit of ordnance equipment. In addition, other ordnance pamphlets contain more general information dealing with a type or class of equipment, such as OP 3000, Weapon Systems Fundamentals, or such data as range tables and nomenclature lists. Ordnance pamphlets are numbered serially, and are listed by both number and subject in OP O, Index of Ordnance Publications.

Ordnance Data (NavOrd OD) are pamphlets which generally contain reports of ordnance inspection and test data, and ordnance equipment lists. ODs are indexed in OP O. An OD referred to in this test is OD 3000, Lubrication of Ordnance Equipment.

OPNAV 34P1, United States Navy Safety Precautions, covers the whole field of Navy safety, ashore and afloat.

The books mentioned above may be obtained from your education officer of your ship or station, or from your leading petty officer.

The United States Armed Forces Institute (USAFI) provides opportunities for military personnel to continue their education while they are on active duty with the Armed Forces of the United States. See your education officer about the details of taking courses. If there are enough interested students aboard ship (or on the base) a group study course can be arranged.

Training films are a valuable source of information on many technical subjects. A selected list of training films that may be useful to you is given in Appendix I of this training course. Other films that may be of interest to you are listed in the United States Navy Film Catalog, NavPers 10000 (Revised).

CHAPTER 2

SERVOMECHANISM DEVICES (PART I)

Servomechanisms (hereafter called servos for short) are an important part of almost every piece of fire control equipment. They are used to automatically position gun mounts, missile launchers, radar antennas, and computing mechanisms. They aid in the control of guided missiles, and play an important role in ship navigation. In fact, it is difficult to find an equipment in which some type of servo is not used.

In Fire Control Technician 3, NavPers 10173-A, you learned about servos in computers. Servos that find application in other fire control equipment operate in the same general manner as the basic position servo described in the earlier text.

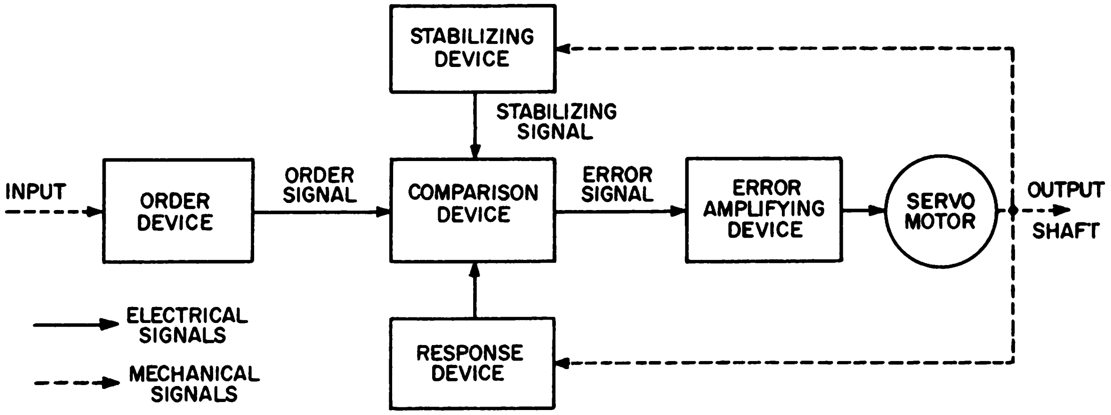
This chapter and chapter 3 describe the various mechanical and electrical devices used in all types of servos. But before we take up this subject, a brief review of servos in general is in order. A servo has been described as a mechanism that knows what it should be doing, knows what it is actually doing, and constantly works to make the two agree. In every servo the output is a shaft rotation which represents the input. For every servo there is a mechanical or electrical order (sometimes called command or input) signal indicating where the output shaft should be and a mechanical or electrical response (commonly called feedback) signal indicating where the output shaft actually is.

Any servo can be broken down into six functional sections. These sections are shown in figure 2-1. In every servo there is a comparison (frequently referred to as an error detector) device which compares the response signal with the order signal and generates an error signal representing the difference, or error, between the actual output shaft position and the position in which the shaft should be. In every servo an amplified version of the error signal continuously controls a servomotor which drives the output shaft in the direction to correct the error. A stabilizing device is usually included to reduce the tendency of the output shaft to overshoot and "hunt" about the correct position. The servo, therefore, constantly strives to eliminate the error and make the output a true representation of the incoming order signal.

For the purpose of this book, servos are divided into three types: positioning, velocity, and computing. The function of the positioning servo is to have the position of the output equal to the input order. The error signal is then the difference between the two positions. In a velocity servo, the velocity of the output, NOT its position, is compared with the order signal. The error exists until the velocity of the output is equal to the ordered input velocity. The computing servo makes a desired mathematical computation from information put into it. The answer is delivered in mechanical or electrical form, or a combination of the two.

SENSING ELEMENTS

This section deals with devices that measure, convert, or sense the INPUT and OUTPUT of any servo, and express them in suitable form. The more common types of these devices convert motion into corresponding electrical energy. These devices are part of a class called transducers. This book will not attempt to put the units treated here into any rigid classification system. Instead, some of the more common terms used by manufacturers and the Navy to classify these devices are mentioned so that you can become familiar with a wide variety of nomenclature. For example, a potentiometer is sometimes classified as a transducer because it can change mechanical energy (used to turn its slider shaft) into electrical energy which is picked off at its terminals. Pots can be classified as error detectors or comparators. They are also used to "pick off" a voltage or to "sense" a change in position of an object.



55.1

Figure 2-1.—Basic servo, block diagram.

POTENTIOMETERS

In servos the input information is usually in the form of a voltage or shaft position. The error signal to the servoamplifier is normally an electrical signal. The feedback or response may be a voltage or a mechanical quantity. You can see that some energy-converting device is required in almost any servo, as well as a device which measures position of the input and output. A potentiometer is one of the simplest means of accomplishing these functions. Figure 2-2 shows a servo with two pots. Pot A is used to convert a mechanical input into an electrical signal proportional to the input's position. Pot B converts a mechanical output into an electrical response signal so that subtraction may be made in the summing network to form the error signal. Note that the error detector or summing network requires two signals in the same energy form; therefore, the mechanical input and output of this servo must be changed (transduced or converted) to electrical energy.

TYPES OF POTENTIOMETERS

There are two basic types of potentiometers: ROTARY and TRANSLATORY. Most of the pots used in fire control equipment are the rotary type, in which the slider motion is rotary. The slider in the translatory pot moves back and forth. The translatory type has limited application in the ordnance field, and will not be discussed here. The basic rotary type can be broken down in two sub-types: the SINGLE-TURN pot and the MULTITURN pot.

The single-turn pot is designed so that its slider will turn through one full revolution (360°) or less. Multiturn pots have their stops set so that the slider can rotate through 60 or more revolutions.

Linear Pots

A linear pot has its resistance element distributed evenly about and on its mandrel; thus each turn has the same amount of resistance. As the input shaft is rotated, the slider will touch various turns and cause a change in resistance between the slider and the end of the potentiometer. With the potentiometer energized, the voltage output will vary in a linear fashion as the slider is moved from one end to the other, because the voltage is distributed equally across each turn. Therefore, a linear potentiometer is one whose voltage output varies linearly with the mechanical motion of the slider.

Nonlinear Pots

A nonlinear pot is one whose voltage output is proportional to a specific function (other than linear) of the mechanical motion of the slider. Nonlinear pots are sometimes referred to as shaped or tapered pots because the resistance element is wound on specially shaped mandrels. Each turn has a different length of wire. Thus, the total resistance is distributed unevenly throughout the length of the pot. With the pot energized, the voltage output will vary in a nonlinear fashion as the slider is moved from

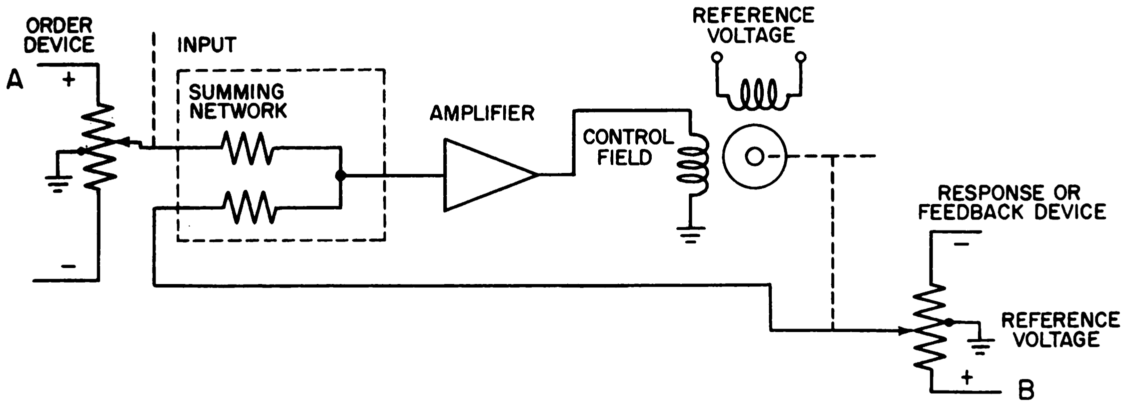


Figure 2-2.—Servo with potentiometer inputs.

55.2

one turn to another. Nonlinear pots can be constructed to produce practically any function such as sine, cosine, and tangent.

POT CONSTRUCTION

Most of the pots used in servos are wire wound. The resistance wire is closely wound around a plastic form called a card or mandrel. The wiper or brush glides along the resistance wire, moving from turn to turn. The potentiometer cards are flat and rectangular, rather than cylindrical. The card is transformed into a cylinder by means of a turnbuckle arrangement.

If you examine a card that has been opened and straightened out, you can easily visualize what happens when the wiper contacts each turn in succession. If the wire is of uniform size and evenly wound, and the card is of uniform width throughout, the movement of the wiper from one turn to the next will add equal amounts, or increments, or resistance between the wiper and one end of the winding, while simultaneously removing equal amounts of resistance from the other end. Moreover, since the voltage drops along the winding are proportional to the resistance, the voltage picked off by the wiper increases in equal increments from zero at one end of the resistance element to maximum value at the other.

Sine and Cosine Pots

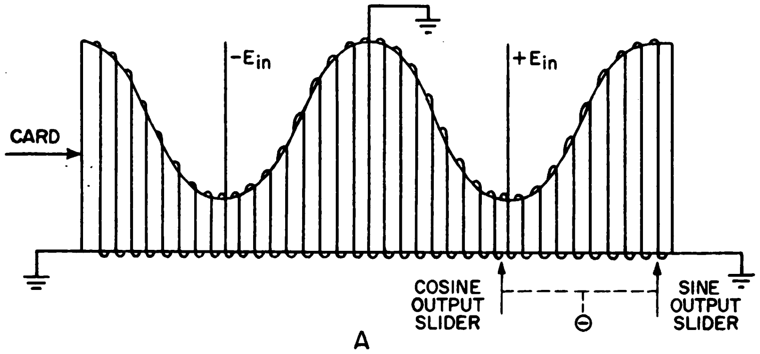
These specially constructed nonlinear potentiometers can be used to generate voltages proportional to the sine and cosine function of an input variable which appears as a mechanical rotation. This type of pot is sometimes called a function generator.

The pot is constructed so that the width of the pot card is made proportional to the sine or cosine function. The resistance element is wound in a continuous layer around the card. The ends of the card are then joined together, forming a cylinder with two lobes. The ends of the resistance elements are also joined together; thus continuous rotation of the pot shaft is possible.

The high points, or lobes, of the cylinder are connected to ground. A positive voltage is connected to one of the low points and a negative voltage to the other. The sine and cosine outputs are obtained simultaneously by having two sliders 90° apart, connected mechanically as a single unit but electrically isolated from each other and from the potentiometer shaft.

The pot shaft is shown in figure 2-3A in its zero position. The sine output is zero volts because the slider is in contact with a grounded portion of the resistance element. The cosine output is a maximum positive voltage because the slider is in contact with the positive voltage. Rotation of the shaft will produce voltages that are proportional to the sine and cosine functions of the mechanical input. The polarity of the output voltages will be the same as the signs of the sine and cosine functions for all four quadrants, as shown in figure 2-3B.

Figure 2-4 shows another type of sine and cosine pot. This type has its resistance element wound in a single layer on a flat rectangular card. The two sliders are rotated by a



QUADRANT	SIN O		COS O	
	FROM	TO	FROM	TO
I 0° TO 90°	0	1.0	1.0	0
II 90° TO 180°	1.0	0	0	-1.0
III 180° TO 270°	0	-1.0	-1.0	0
IV 270° TO 360°	-1.0	0	0	1.0

B

Figure 2-3.—Combination sine and cosine pot. 55.3

mechanical shaft, which is mounted in the center of the card. The two sliders are mounted 90° apart; one will provide the sine output, the other the cosine output.

When voltages of opposite polarities are connected to the two ends of the resistance element, a constant potential gradient will exist along the card from one end to the other. If the resistance element is grounded at the center of the card, and the sliders are rotated in a circular path about this point, the output voltages are the sine function and cosine function of the angle of rotation.

POT CHARACTERISTICS

Linearity

In general, linearity is just any straight line relationship. In the graph, shown in figure 2-5, Y is said to vary linearly with X. This graph could represent the linearity characteristic of a perfectly linear potentiometer if Y equals the voltage output and X equals the shaft rotation of the potentiometer. In other words, for the same increment of shaft rotation the same increment of voltage output would be obtained. However, due to the construction of pots and the inaccuracies of the resistance element, the perfect pot is never attained. Each linear pot does have some deviation from the computed voltage; therefore potentiometer linearity deviation is the maximum deviation from the best straight line that can be drawn through the points of a voltage versus shaft rotation graph. This deviation is generally expressed in percentage of total voltage, and is usually shown on the housing of the pot. When the straight line originates at the origin, the linearity of the pot is called zero base linearity, or absolute linearity. In figure 2-6, the pot output curve varies from the straight line. The deviation never exceeds 0.01 volts, therefore the curve represents a voltage of .001 with a maximum supply voltage of 10 volts. From the formula shown in figure 2-6, we can determine that the linearity of the pot is 0.1 percent.

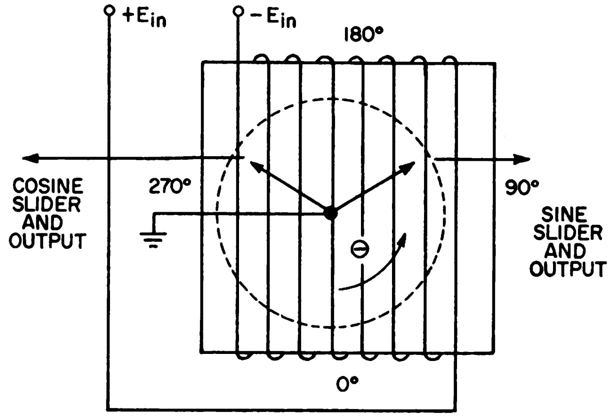
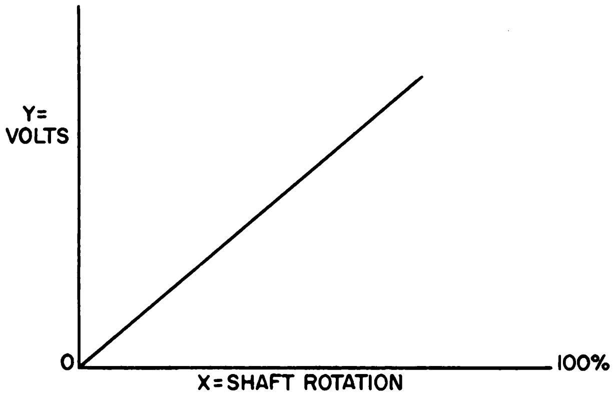


Figure 2-4.—Sine and cosine pot—rectangular card type. 55.4

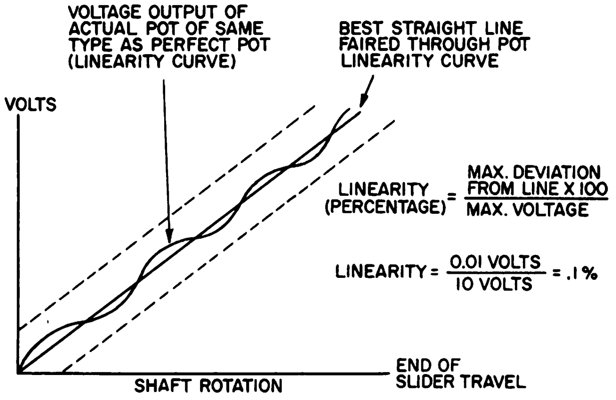
Resolution

The resolution of a pot is determined by the way its resistance element is constructed. In most cases, the resistance element is composed of coiled resistance wire. As the slider is moved across these coils, the resistance tapped off



55.5

Figure 2-5.—Perfect linearity curve.



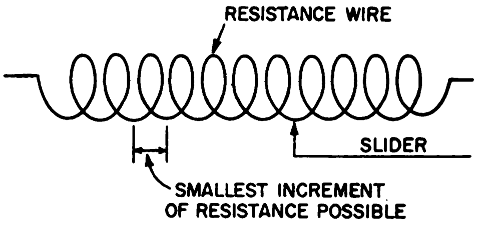
55.6

Figure 2-6.—Zero base linearity curve.

will vary in small steps, called increments. (See figure 2-7.) Thus, resolution is the term used to described the smallest increment of resistance as the slider moves from turn to turn.

The increments will be the amount of resistance of one coil of the resistance wire. The size of these increments with respect to the size of the resistance element (end to end resistance) determines the resolution of the pot. Thus, resolution equals resistance of the element divided by the smallest increment possible.

Since the resistance of a pot changes in small steps, it is only natural that the voltage output between the slider and either end terminal will change in increments or small steps. Each step is equal to the voltage difference existing between adjacent turns. A pot having 1000 turns of wire in the resistance element is said to have a



55.7

Figure 2-7.—Reason for pot resolution.

resolution of 0.1 percent. To express resolution in terms of percentage, you can use this simple formula: resolution (percent) $= \frac{100}{N}$, where N equals the number of turns in the resistance element. A resolution of 0.1 percent means that the smallest change in the output voltage is 1/1000 of the input voltage. When proper operation of the servo requires high resolution, this can be attained by using a pot with closely spaced turns of fine wire, and with a multiturn shaft.

Loading Effect

To show you what is meant by loading, consider a linear pot with a fixed voltage applied to the end terminals. This setup is shown in figure 2-8. The voltage output at the slider will not vary linearly if current is drawn through the slider. Thus, a pot is said to be loaded if the slider draws current. Of course the slider will always draw some current, but in precision pots it should be held to a minimum. This is done by feeding the output of the pot into a high resistance load—a load whose resistance is high compared to the pot resistance.

The graphs in figure 2-8 illustrate the loading effect on a pot with a single input. Part A of figure 2-8 shows that with a high resistance load the loading effect is negligible. But, if the load has a low resistance as shown in part B of the figure, then the loading effect is great and the output voltage will change considerably. Notice that maximum loading will occur at two-thirds of maximum rotation, as shown in figure 2-8C. Loading effect is kept to a minimum by design but you can see what would happen if a casualty caused the effect of loading. Table 2-1 has been calculated for other positions of the pot's slider shown in figure 2-8C.

Noise

Of all the pot characteristics, pot noise can be the most important to a technician. Resolution, linearity, and loading error are minimized by the pot manufacturer. So is noise, but normal pot wear will increase its effects so that some servos will become completely unstable or inoperative.

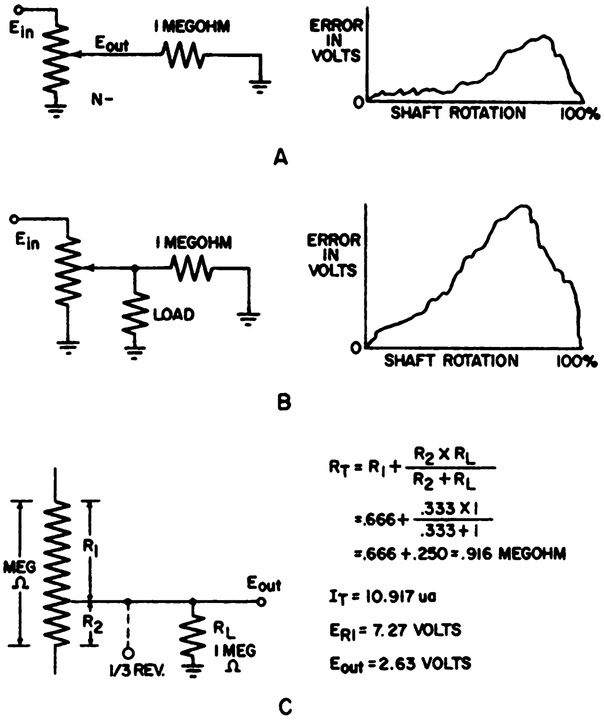
Table 2-1.—Output Voltages for Various Positions of Pot Slider.

Amount of Rotation	E_{out} should be	Actual E_{out}	Error in volts
0 rev.	0.00 volt	0.00 volt	0.00
1/3 rev.	3.33 volt	2.63 volt	0.70
1/2 rev.	5.00 volt	4.00 volt	1.00
2/3 rev.	6.67 volt	5.46 volt	1.21
3/4 rev.	7.50 volt	6.32 volt	1.18
9/10 rev.	9.00 volt	8.26 volt	0.74
1 rev.	10.00 volt	10.00 volt	0.00

These figures have been based on a one turn pot for 100% of rotation.

Noise is any fluctuating distortion in the output signal of the potentiometer. Figure 2-9 shows a sine wave with a noise component. Noise from a potentiometer source is caused by several factors. Voltage variations may be caused by resistance changes between the slider contact and the resistance element. The tension of the slider may vary to change the resistance between the two elements. Foreign matter between the slider and resistance element will cause resistance changes in the pot circuit; thus, voltage fluctuations are generated. In wire-wound pots, noise is generated because of the step action as the slider moves from one resistance coil to another.

Pots used in computing servos should be replaced when they become noisy. In other servos, noise may not have too much effect on proper servo operation. The best way to detect pot noise is to look at the voltage output of the suspected unit on an oscilloscope.



55.8

Figure 2-8.—Loading effect on single-input pot.

VARIABLE TRANSFORMERS

A variable transformer is a device in which the magnetic coupling (primary and secondary) between a set of stator coils and a set of rotor poles (which may or may not be wound) can be varied by moving either the rotor shaft, the stator assembly, or both. Variable transformers, like the other devices mentioned here, may be classified by many different methods. A few of these are: (1) application, (2) construction, (3) principles of operation, and (4) manufacturers' trade names.

These devices may be used in servosystems to perform many functions. They are used to transmit information between remote units of a system. Some examples of data transmission units are synchros, resolvers, and E-transformers. Variable transformers, like pots, serve as position-measuring devices which indicate the position of the input and output shafts of a servo. In addition, variable transformers can change mechanical information into electrical information and, conversely, change electrical information into mechanical. Moreover, some of these units, such as resolvers, perform mathematical operations.

SYNCHROS

Synchros are variable transformers that find extensive application in positioning servos,

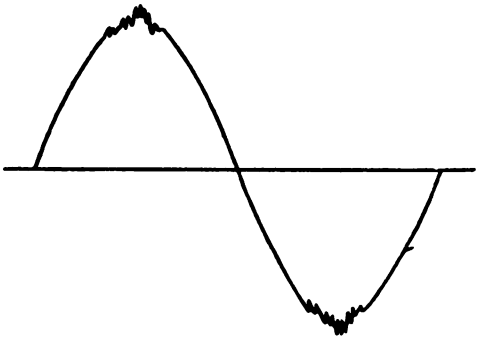


Figure 2-9.—Pot noise as seen on an oscilloscope. 55.9

especially the combination made up of the synchro control transmitter (CX) and synchro control transformer (CT). This team provides the data transmission and error detection functions in servosystem operation.

You learned a great deal about synchro operating principles in Fire Control Technician 3, NavPers 10173A. One thing in particular you learned was that a synchro system consisting of a torque synchro transmitter and torque synchro receiver is not able to position a heavy load because the receiver is incapable of producing strong enough torque. The way to overcome this limitation is to replace the receiver with a control transformer, amplifier, and motor. You have probably recognized the essential components of a servosystem as they were outlined in the preceding sentence.

The synchro control transformer is the heart of most servosystems. Its construction, operating principle, and general application are the subjects of this section.

Control Transformer Construction

The stator of the synchro control transformer (hereafter called CT for short) is very similar to stators of other synchros, with one exception: the windings are made of many more turns of finer wire. The reason for the increased number of turns is to make the impedance of the stator high. The need for the high impedance is to limit the flow of current through the stator so that several CTs may be connected to the same transmitter. The rotor of the CT has one series winding just like the rotor of the other synchro units. However, the CT's rotor is completely round, not bobbin-shaped as in the synchro motor. The round shape prevents the rotor from being attracted by the magnetic field in the stator. As a result, the rotor, if free to turn, will not turn to any particular position as the magnetic field in the stator shifts position. The only torque exerted on the rotor shaft will be due to the mechanical coupling of the shaft to the servo or other gearing.

Control Transmitter Operation

To help you understand the operation of a CT, consider the operation of a control transmitter and CT connected as a system. Figure 2-10 shows the stators of these two units hooked up in the usual manner. Both synchros are shown on electrical zero.

When the rotor of the transmitter is in the zero position, the rotor magnetic field is pointed straight up, as shown in the figure. The voltages applied to the stator windings of the CT will always produce a flux field identical to that in the transmitter. Therefore, the magnetic field in the CT will also point upward. It might be a good idea for you to remember this important point. Notice that the rotor is at right angles to the magnetic field. With the rotor in this position, the induced voltage in the rotor is zero.

When the rotor of the transmitter is turned 60° clockwise, as shown in figure 2-11, the magnetic field in the transmitter and the CT also rotate 60° clockwise. Now a voltage is induced in the CT rotor windings and a voltage appears across the CT R1-R2 terminals. The rotor of the CT is wound in such a manner that a clockwise rotation of the magnetic field induces a voltage across the CT rotor leads R1-R2 which is in phase with the a-c supply to the transmitter rotor. This action is shown in figure 2-11. As the rotor of the transmitter turns from zero degrees to 90 degrees, the induced voltage across the rotor of the CT increases from zero until it reaches its maximum value at 90 degrees. The induced voltage across the rotor of the CT can be brought to zero by turning the control transformer through the same number of degrees and in the same direction as the rotor of the transmitter. This action is shown in figure 2-12.

If the rotor of the transmitter is turned in a counterclockwise direction from its zero position, the magnetic field in the CT will also rotate counterclockwise through the same number of degrees as the transmitter shaft. Since the magnetic field in the stator of the CT now cuts through the rotor in the opposite direction, the induced voltage in the rotor will now be out of

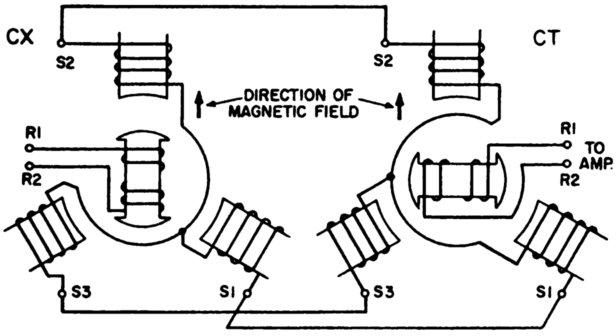


Figure 2-10.—Synchro control transmitter and synchro control transformer at electrical zero. 55.10

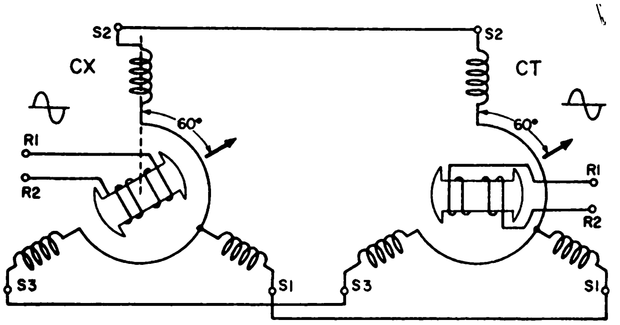


Figure 2-11.—Direction of flux fields, CX rotor at 60°, CT rotor at 0°. 55.11

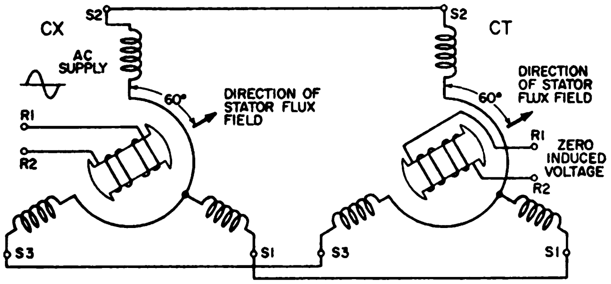

CX
S2
S2
CT
AC SUPPLY
60°
DIRECTION OF STATOR FLUX FIELD
60°
DIRECTION OF STATOR FLUX FIELD
R1
R2
R1
ZERO INDUCED VOLTAGE
R2
S3
S1
S3
S1

Figure 2-12.—Direction of flux fields, CX rotor at 60°, CT rotor at 60°. 55.12

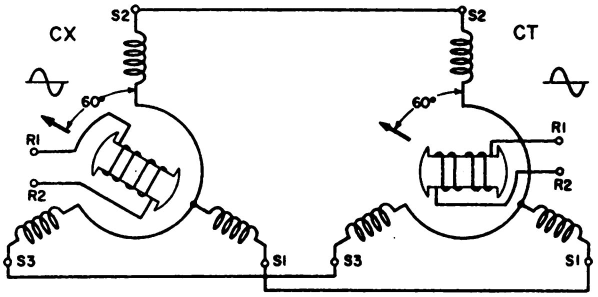


Figure 2-13.—Direction of flux fields, CX rotor at 300°, CT rotor at 0°. 55.13

phase with the a-c supply to the transmitter, as shown in figure 2-13. The induced voltage across the rotor of the CT can again be brought back to zero by turning the CT rotor through the same number of degrees and in the same direction as the rotor of the transmitter, as shown in figure 2-14.

REDUCING SYNCHRO ERROR

All synchro units, regardless of how carefully they are made, will introduce a certain amount of error into the system in which they are placed. The inaccuracy is usually caused by gearing and electrical tolerances as well as friction. The following example will illustrate for you how a tolerance factor in a synchro unit can affect the accuracy of a servosystem.

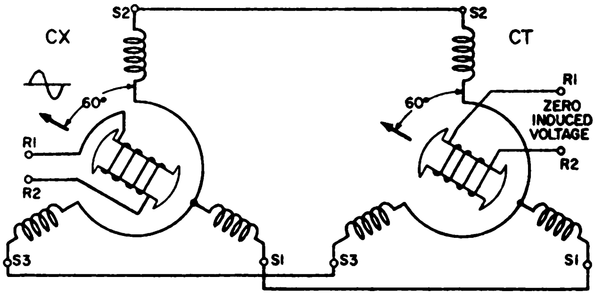


Figure 2-14.—Direction of flux fields, CX rotor at 300°, CT rotor at 300°. 55.14

One-Speed Synchro Systems

The block diagram in figure 2-15 illustrates a simple positioning servo which positions an antenna by means of a handcrank at a below deck console. It is assumed that the synchro transmitter is geared directly to the handcrank, and that the gear ratio between the two is one-to-one.

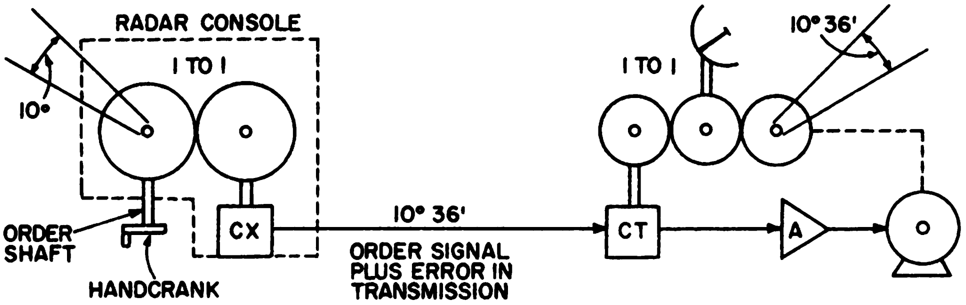


Figure 2-15.—Error in synchro transmission. 55.15

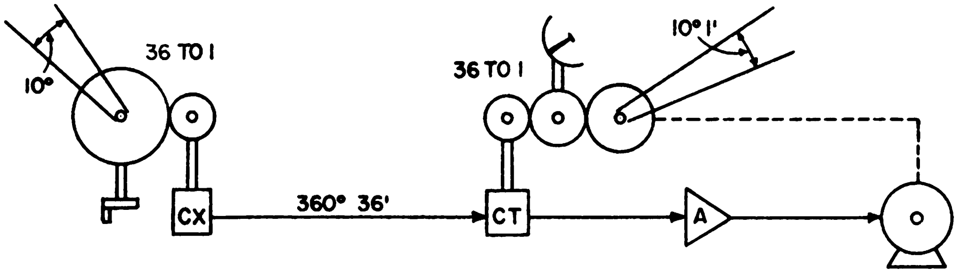


Figure 2-16.—Decreasing synchro transmission error by increasing gear ratio. 55.16

The gear ratio between the control transformer and the antenna is also one-to-one. If the synchro transmitter has an error of plus or minus 36 minutes of angle, the final position of the antenna must be in error by the same amount for every position of the handcrank. For example, if the handcrank is turned 10°, the synchro transmitter will transmit an electrical signal 10° plus 36 minutes to the CT. When the servosystem reaches correspondence, the final position of the rotor of the control transformer must also be 10° plus 36 minutes in order for the error signal to be zero. This means that the load will be positioned at 10° plus 36 minutes, since the gear ratio between it and the CT is one-to-one. The position of the load is therefore in error by 36 minutes in relation to the input signal of 10 degrees. You can see that in the above setup, which is called a one-speed transmission, every transmitted signal can have an error of as much as 36 minutes.

36-Speed Transmission

The way to minimize the inherent errors in synchro systems is to make the synchro units turn a lot faster than the input shaft (in this case, the handcrank) and the load. This can be accomplished by increasing the gear ratio between the handcrank and the synchro transmitter and between the load and the control transformer. For example, if the gear ratio is increased 36 to 1, the error will be decreased to 1/36 of its former value. The diagram in figure 2-16 shows the same servo as before; the only difference is the increase in the gear ratio as shown. Now, if the handcrank is turned 10°, the shaft of the synchro transmitter will turn 360° plus 36 minutes, the inherent error in the synchro system. In order for the CT shaft to turn through the same angle to bring it into correspondence with the transmitter and thus reduce the error signal to zero, the load must rotate through 10° and one minute. This value of 10° and 1 minute is stepped up by the gear ratio to 360° and 36 minutes as shown. The 36-to-1 gear ratio has therefore reduced the error from 36 minutes to one minute.

The 36-to-1 gear ratio also increases the sensitivity of the servo at times when the angular difference between the input and the load is very small. The small angle is actually stepped up 36 times before it reaches the servoamplifier where it is amplified to drive the servomotor. The 36-to-1 gear ratio is called a 36-speed transmission.

DISADVANTAGES OF 36-SPEED SYNCHRO TRANSMISSION.—The disadvantage of the 36-speed transmission is that the servosystem is no longer self-synchronous. In the one-speed transmission, the load is synchronized with the input shaft (handcrank) at only one point. In other words, there is only one position the load can assume which will allow correspondence between the rotor of the CT and the rotor of the transmitter. However, in the 36-speed transmission, the load can be in synchronization—that is, the CT and the transmitter can be in correspondence and the input to the servoamplifier be reduced to zero—at 36 different positions of the load for any one position of the handcrank. See figure 2-17. For example, if the handcrank is at 0°, the load would be synchronized at 0°, at 10°, at 20°, and so on in steps of 10 degrees. In each of these positions of the load, the angle of the CT is stepped up 36 times so that it is an integral multiple of 360°—bringing the CT into correspondence with the transmitter in each case. If the load and the handcrank are more than 5° apart when the system is turned on, or if the load lags the handcrank by 5° or more, correspondence will be established at one of these "false zeros" and the system will lock out of synchronization.

Combining the One-Speed and 36-Speed Transmissions

Although the 36-speed transmission provides high accuracy in a serosystem, it is not normally used by itself since it does not provide complete synchronization of the input and load at all times. The 36-speed transmission must be combined with a low speed transmission system to give accuracy as well as synchronization at all times. The combination of the two is called a two-speed or dual-speed synchro transmission.

The term 2-speed transmission is confusing—it has nothing to do with gear ratio—it simply means that two systems are combined to perform the data transmission function. You will see the term 2-speed used in many text books on servos and synchros, so make sure you know the difference between 1-speed, 2-speed, 36-speed, 72-speed, and other transmission speeds. To avoid confusion, the term dual-speed transmission will be used in the rest of this text.

A servosystem which contains a dual-speed synchro transmission is set up as indicated in figure 2-18. The low speed synchro transmission, or coarse control as it is sometimes called, consists of a transmitter and a control transformer which are geared directly at a one-to-one ratio to the input and load respectively. The coarse control has the full 36 minutes of error, but it has only one point of synchronization. The high speed synchro transmission, or fine control, consists of a transmitter and control transformer which are geared at a 36-to-1 ratio to the input and load respectively. For clarity, let's further assume that the fine system is errorless. Both the coarse and fine controls apply their inputs to the servoamplifier through a switching device which automatically selects which input is to supply a signal to the servoamplifier (more about this later). When the load and the input are a comparatively large number of degrees out of correspondence, the switch selects the coarse control to bring the load close enough to true synchronization so that the fine control can take over. The fine control usually takes over when the load is more than 2 degrees but less than 5 degrees of correspondence. In this manner, the coarse control produces approximate correspondence and makes sure that the load and the input are synchronized at the right point. The fine control produces accurate correspondence once the coarse control has determined the correct point for exact synchronization.

Although only a 36-to-1 fine control was mentioned in the explanation, there are many different fine control ratio systems in use, depending on the degree of accuracy required in the particular servo in which the fine control is situated. The most common ratios found in fire control systems are 72 to 1, 36 to 1, and 18 to 1. The synchro units associated with these systems are called "high speed" synchros.

The coarse control may be 2 to 1 in addition the 1-to-1 ratio previously mentioned. The coarse control synchros are usually called "low speed" synchros.

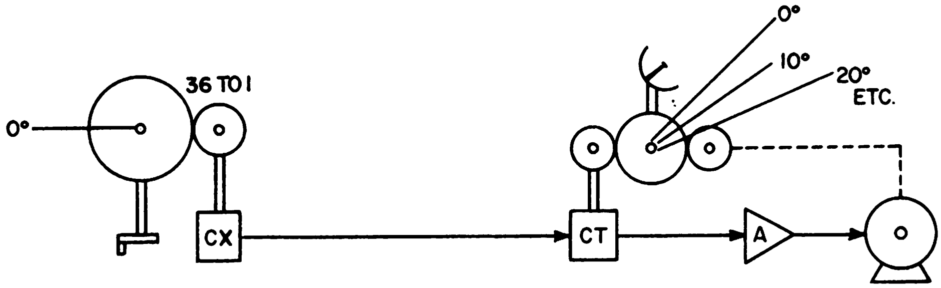


Figure 2-17.—Synchro transmission system geared 36-to-1 can synchronize at any multiple of 10 degrees.

55.17

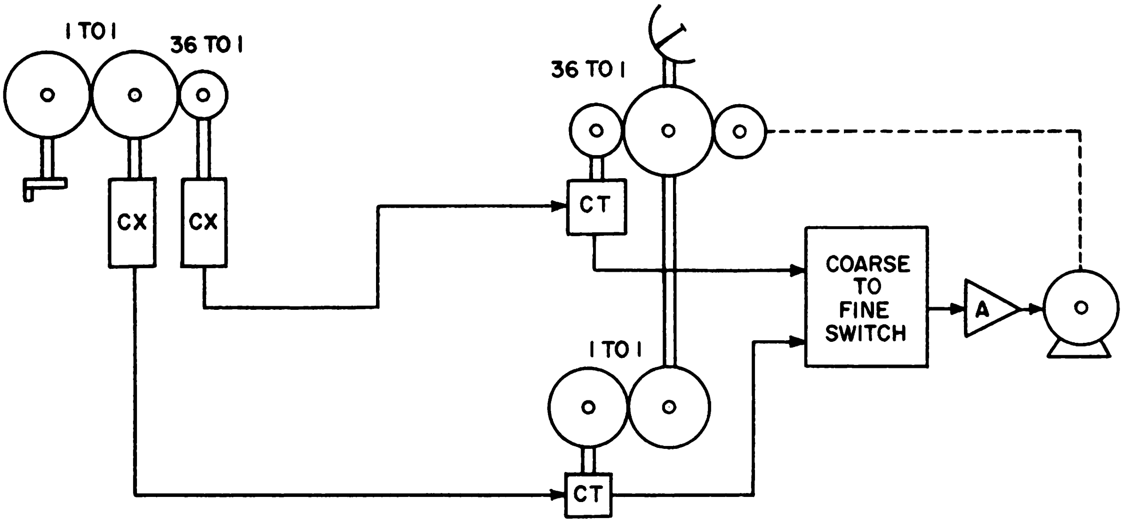


Figure 2-18.—A dual-speed synchro transmission servosystem.

55.18

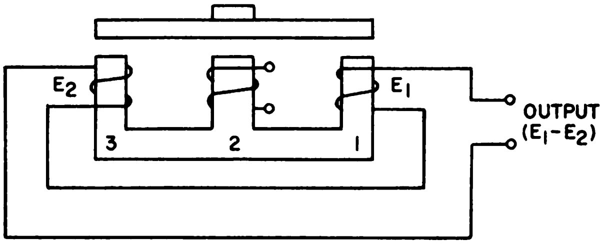
E-TRANSFORMERS

E-transformers, like synchros, also operate as variable transformers. They have many applications in the fire control field. They are used in some stable element level and crosslevel servos. This device also serves as a pickoff device in director-positioning servos. As its name implies, the E-transformer operates on the transformer principle.

The simplest form of the E-transformer is shown in figure 2-19. An alternating voltage is applied to the primary coil on the center pole of the laminated E-shaped core. Two secondary coils (1 and 3 in the figure) are wound in series opposition on the outer poles of the structure. The magnetic coupling between the primary (coil 2) and the two secondaries varies with the position of the armature. The armature can be displaced laterally in either direction in the magnetic circuit. This changes the reluctance between either pole and the armature.

When the armature is located in the center of the structure, as shown in the figure, equal voltages are induced in the secondary coils, and the difference between them is zero. Thus, the voltage at the output terminals is also zero.

But if the armature is moved, say, to the right, as shown in figure 2-20, the voltage induced in coil 1 increases, while the voltage induced in coil 3 decreases. The two voltages are then unequal, so that the difference is no longer zero, and a net voltage results at the output terminals. A sense of direction is provided since the output voltage changes phase as the armature passes through the null (center



55.19

Figure 2-19.—Basic E-type transformer with armature at null (zero) position.

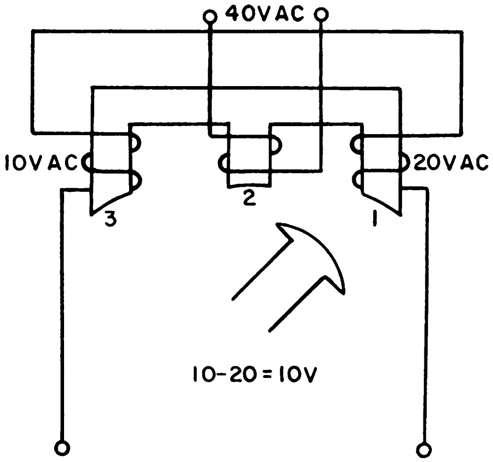


Figure 2-20.—Basic E-transformer with armature offset from center position. 55.20

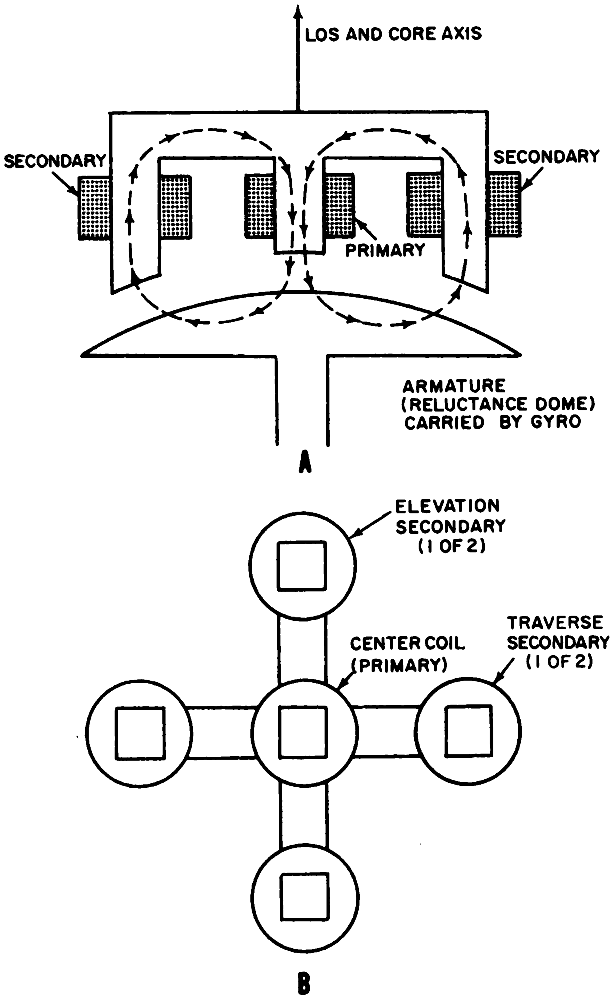
position). The output voltage phase will be either in phase with the primary voltage or 180° out of phase. The amplitude of the output voltage is proportional to the amount the armature moves back and forth from the center position.

Crossed-E Transformer

E-type transformers are used in fire control equipment to measure angular movement; therefore, the basic E-transformer just described must be altered slightly to perform this function. If you place two E-transformers at right angles to each other and replace the bar armature with a dome-shaped one, you have the basic configuration of what is known as the crossed-E transformer, or pickoff. In most applications the dome-shaped armature is attached to a gyro, and the core assembly is fixed to a gimbal which is the servo load.

The crossed-E transformer assembly consists of five legs (poles). Each leg is encased by a coil. The coil around the center leg is the primary, which is excited by an alternating voltage. The remaining four coils are the secondaries. Figure 2-21A shows a cross-sectional view of the crossed-E transformer and the flux paths through the armature. Part B of figure 2-21 shows how the crossed-E transformer looks from the front. From this view you can see how it gets the name, crossed-E.

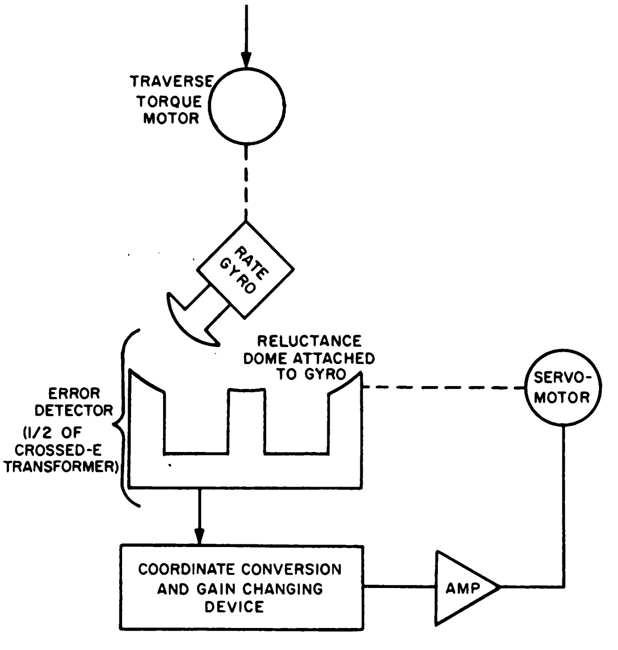
To understand the operation of the crossed-E transformer, let's see how it works in a typical director-positioning servo. Figure 2-22. shows a simplified block diagram of a train power drive.



A. Cross section
B. Front view

55.21A

Figure 2-21.—Crossed-E transformer.

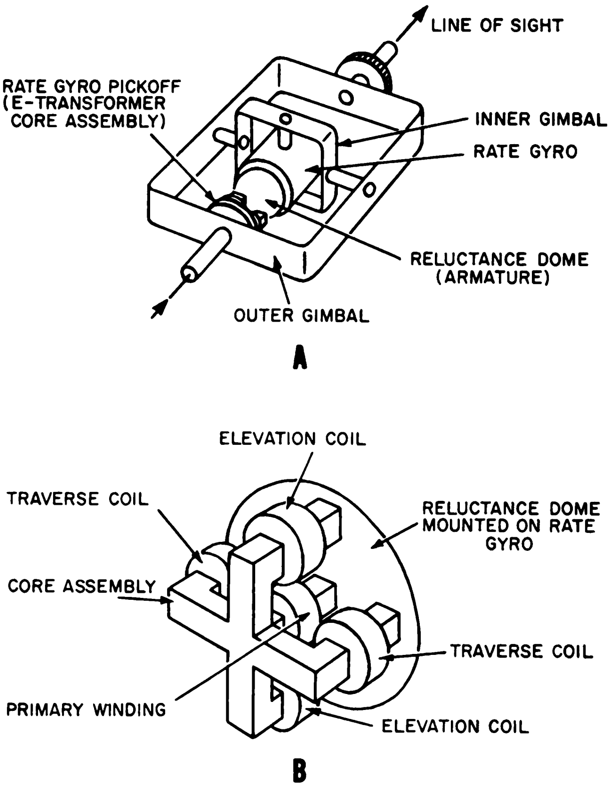

TRAVERSE TORQUE MOTOR
RATE GYRO
RELUCTANCE DOME ATTACHED TO GYRO
SERVO-MOTOR
ERROR DETECTOR (1/2 OF CROSSED-E TRANSFORMER)
COORDINATE CONVERSION AND GAIN CHANGING DEVICE
AMP

55.22

Figure 2-22.—Train power drive (positioning

Let us assume that the director is tracking, and that the target is moving to the right. The current (which represents tracking error) through the traverse torque motor will cause the motor to precess the gyro clockwise as indicated in figure 2-22. The gyro is positioned slightly to the left of center of the transformer. The core assembly is carefully positioned on the gyro gimbals to that the core axis is parallel to the line of sight. You can see the relationship in figure 2-23.

When the reluctance dome, and thus the gyro spin axis, is to the left of center, more flux links the left leg with the primary coil and the voltage induced in the left secondary increases. The right leg has fewer flux linkages with the center coil; therefore, the voltage induced in the right coil will be less than that in the left coil. Thus there will now be a net voltage out of the pickoff. The phase of the output will be that of the larger voltage. It follows that if the gyro were torqued to the right, the opposite condition would exist. From this brief description, you can see that the crossed-E transformer works on the same fundamental principle as the basic type described earlier. The major difference between the two is in shape and the number of secondaries, and in the fact that the armature has universal movement.



A. Location of components
B. Relationship between core assembly and reluctance dome

Figure 2-23.—Cross-E transformer in director-positioning servo.

55.23

The signal from the transformer ultimately drives the director until the axis of the center leg of the core assembly is in coincidence with the axis of the reluctance dome. When this occurs, the line of sight is on target and no radar tracking error exists. Note again that this servosystem, in block form, contains all the essential parts of a basic servo.

Stable Element Crossed-E Transformer

Another application of crossed-E transformers as a pickoff or error detector is in stable element servosystems. Figure 2-24 shows a simplified block diagram of a level servo. The crosslevel servo is identical but is deleted for clarity.

Roll or pitch movement, or both, of the ship displaces the pickoff core from its position directly over the gyro. The vertical axis of

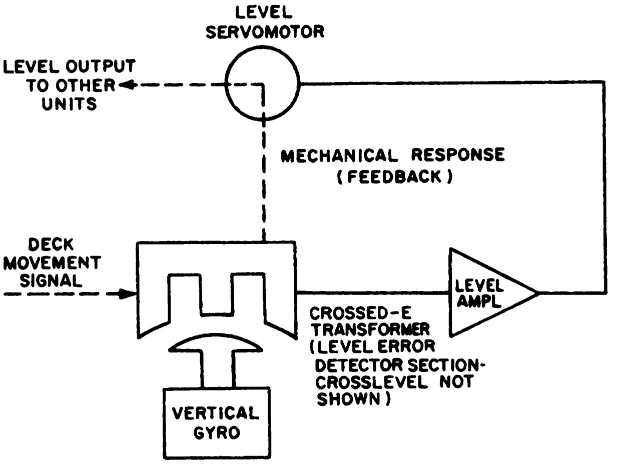

LEVEL SERVOMOTOR
LEVEL OUTPUT TO OTHER UNITS
MECHANICAL RESPONSE (FEEDBACK)
DECK MOVEMENT SIGNAL
LEVEL AMPL
CROSSED-E TRANSFORMER (LEVEL ERROR DETECTOR SECTION-CROSSLEVEL NOT SHOWN)
VERTICAL GYRO

Figure 2-24.—Simplified block diagram of a stable element level or cross level servo. 55.24

the gyro represents the vertical. Any slight displacement of the core, and thus of the secondary windings, causes generation of an error signal. The level and crosslevel servosystems operate in response to these error signals and return the pickoff core to its original position. The amount and direction of travel of the pickoff core is transmitted in the form of synchro signals or appropriate mechanical motion to the equipment being stabilized.

Figure 2-25 shows a cross-sectional view of the pickoff assembly and the flux paths through the pickoff armature. Coil A is the primary coil which induces a magnetic flux in the iron frame (core). The two coils marked B are connected in series and the voltages induced in these coils oppose each other. The same is true for the two coils marked C. The B coils are connected to the input of one servoamplifier, say level, and the C coils are connected to the input to the other (crosslevel) amplifier.

When the axis of the center leg is directly in line with the gyroscope axis, the core is located above the armature as shown in part A of figure 2-25. The reluctance of the flux path from the center leg to each of the other four legs is equal, and the lines of flux through each of the four legs are equal. Therefore, the voltages induced in each of the B and C coils are equal and the net voltage in each pair of coils is zero, because the voltages oppose each other. When the ship's motion causes the pickoff coil assembly to move with respect to the vertical gyroscope axis, as shown in figure 2-25B the reluctance of the flux path from the center leg to each of the B legs is no longer equal. Instead, the leg which moves closer to the center of the pickoff armature will have an increase in the number of lines of flux passing through it. Hence, unequal voltages will be induced in the two legs; in this example, the voltage induced in the left B coil would be greater. The net voltage is then applied to its associated servoamplifier.

In this example, it was assumed that the reluctance of the flux path from the center leg of the C legs did not change. Unequal voltages are induced in the two C coils in the same manner by ship's motion at 90° to that affecting the B coils.

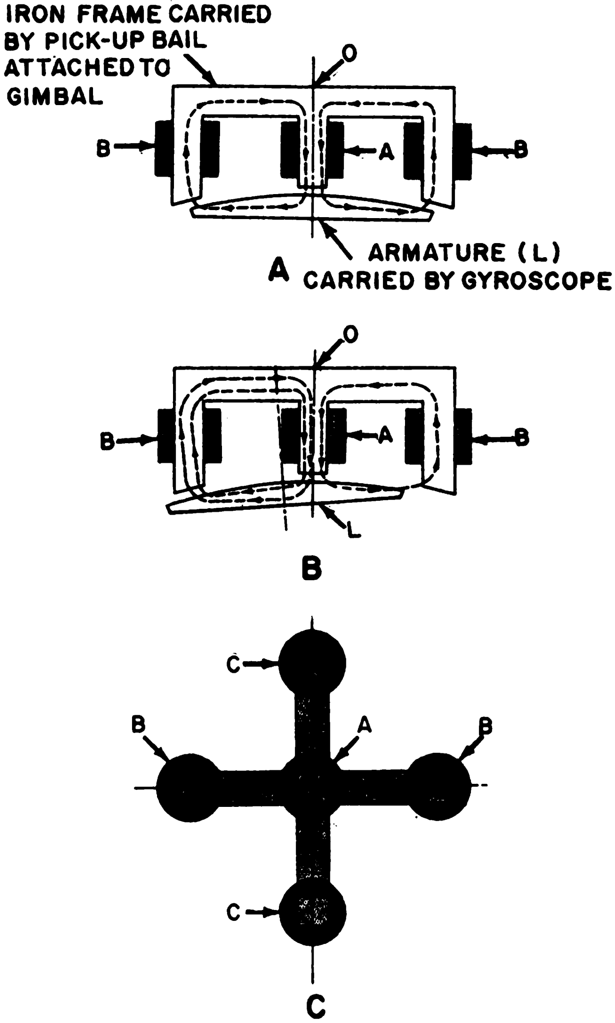

IRON FRAME CARRIED BY PICK-UP BAIL ATTACHED TO GIMBAL
O
B
A
B
A
ARMATURE (L) CARRIED BY GYROSCOPE
O
B
A
B
L
B
C
B
A
B
C
C

Figure 2-25.—Stable element pickoff (crossed-E) assembly. 55.215

E-Transformer in an Antenna-Positioning System

Figure 2-26 shows a simplified block diagram of an antenna-positioning servo. The gyro unit and its associated E-transformer is located in a lead-computing sight on a director. The antenna with its associated E-transformer unit is attached to a gun mount. The block diagram could represent either the train or elevation antenna-positioning servo. Since they are identical, only elevation is described here.

When the director is stationary, no lead angle is generated; the elevation gyro axis and the radar beam axis are parallel to the optical line of sight. For this condition both the gyro pickoff and the antenna pickoff transformer armatures are at their center position. Thus the amplifier receives no signal and the servomotor is stationary.

Now, if the director is elevated, as when tracking a target, the elevation gyro will precess and move the armature from its center position. A signal is generated by the gyro unit E-transformer. The signal is transmitted to the amplifier. It is amplified and then passed to the servomotor, which drives the radar antenna to bring its axis parallel to the optical line of sight. Antenna movement displaces the armature of the antenna pickoff transformer. A voltage is then induced in the secondary of the antenna pickoff which is 180° out of phase with the voltage induced in the gyro pickoff, and this signal starts to cancel out the amplifier input signal.

When the radar beam axis has moved so that it is parallel to the lead-computing sight line of sight, the signal at the amplifier input is cancelled (nulled) and the servomotor receives no power from the amplifier, and the motor stops.

THE MICROSYN

The microsyn, shown in figure 2-27, is frequently used as a torquer or pickoff in gyro units in director and antenna-positioning servos. Microsyns are also used in gyro units that are part of inertial guidance systems. The microsyn is an error-detecting, measuring, or similar device which can be used either as a transmitter (signal generator) or a receiver (sometimes referred to as a torquer, torque motor, or torque generator.)

Either unit consists of a bobbin-shaped two-pole rotor and a four-pole stator. The four poles are displaced 90° from each other. A primary coil and a secondary coil are wound on each pole. The rotor has no windings, and serves only to change the reluctance of the magnetic paths between the stator poles. The rotor is mounted on ball bearings. Because if has no winding, no electrical connections, such as brushes or sliprings, are required.

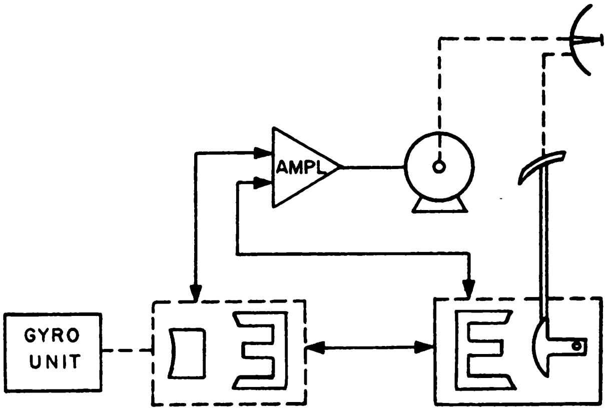
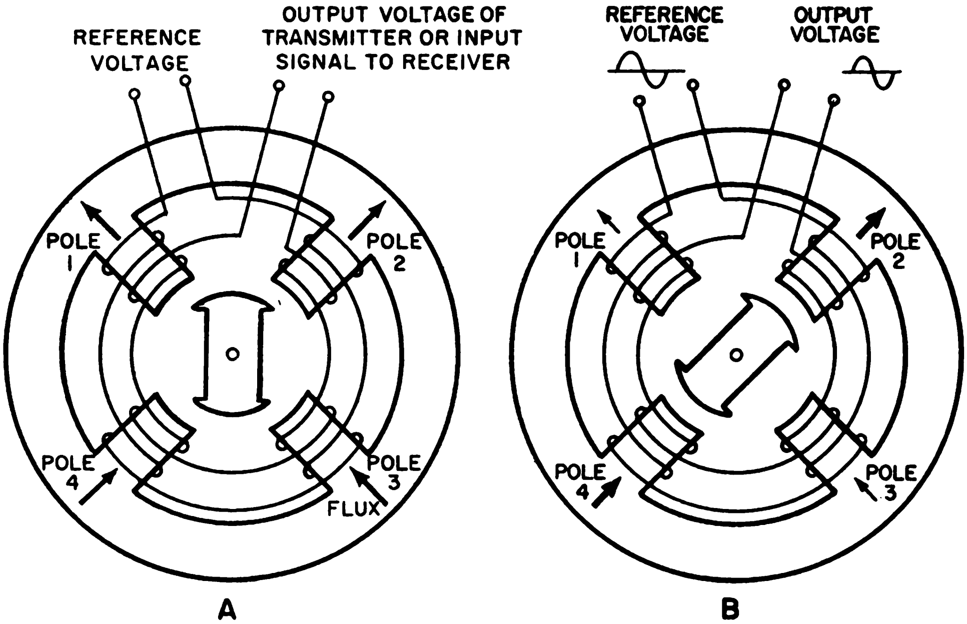


Figure 2-26.—Antenna-positioning servo. 55.25

When the microsyn is used as a transmitter, its output is a voltage whose phase is determined by the direction of rotor movement. The amplitude of the output voltage is proportional to the amount the rotor is displaced. When used as a receiver, its output is a torque—hence the name torquer or torque generator. The direction of the torque is determined by the phase relationship between the two input voltages, and its magnitude is determined by the amplitude of the variable input voltage.

Microsyn Transmitter

In the transmitter or signal generator unit the four primary coils are connected in series and are excited by a 400-cycle reference voltage. Other frequencies are used, but 400 cycles is most common. The coils are wound so that the flux in pole 1 aids the flux in pole 4, and the flux in pole 2 aids the flux in pole 3. When the rotor which is attached, say, to the output shaft of a gyro, is in the zero position as shown in figure 2-27A, equal amounts of rotor iron are under each of the four pole faces. In this position, the pole 1-pole 4 flux through the rotor equals the pole 2-pole 3 flux through the rotor. Equal voltages are now induced in the secondary



A. Rotor at servo
B. Rotor displaced to ight

Figure 2-27.—Microsyn torque or signal generator.

55.26

coils. These four secondary coils are also connected in series. The voltage induced in the pole 1 secondary aids the voltage induced in the pole 3 secondary. The combined voltages in the pole 1 and pole 3 secondaries oppose the combined voltages of the pole 2 and pole 4 secondaries. When the rotor is at the zero position, these two pairs of combined voltages are equal, and the output of the microsyn transmitter is zero.

When the rotor of the microsyn transmitter is turned to the right (fig. 2-27B) by a mechanical input, in this case gyro precession, the amount of rotor iron under poles 2 and 4 exceeds the amount of rotor iron under poles 1 and 3. The total voltage induced in the secondary coils of poles 2 and 4 now exceeds that induced in the secondary coils of pole 1 and pole 3. Under this condition the phase of the output voltage is that of the voltage induced in the secondary cells of poles 2 and 4, and the amplitude of the output voltage is equal to the voltage induced in secondary coils 2 and 4 minus the voltage induced in secondary coils 1 and 3. If the rotor of the microsyn is turned to the left, the magnitude of the output voltage equals the voltage induced in secondary coils 1 and 3 minus the voltage induced in secondary coils 2 and 4. Thus, the microsyn transmitter has an output voltage whose phase is determined by the direction of the rotor displacement from zero and whose amplitude is determined by the amount of this displacement.

Microsyn Receiver

This unit is physically and electrically identical to the transmitter. However, the rotor is free to turn. The rotor can be attached to the input shaft of a rate gyro. When the reference voltage alone is applied to the primary, the fields produced in the four primary coils will position the rotor to zero so that equal amounts of rotor iron are under each of the poles. If a voltage in phase with the reference voltage is applied to the secondary coils, the flux produced in poles 2 and 4 by these coils aids the flux produced by the primary coils. Meanwhile the flux produced in poles 1 and 3 by the secondary coils opposes the flux produced by the primary coils. The magnetic field produced in poles 2 and 4 is stronger than that produced in poles 1 and 3. Therefore a torque, exerted on the rotor, will attempt to increase the amount of rotor iron under poles 2 and 4.

If the phase of the voltage applied to the secondary coils is reversed, the direction of the resultant torque will be reversed. Therefore, it can be said that the microsyn receiver produces a torque whose direction is determined by the relative phase of the reference and signal voltages, and whose magnitude is determined by the amplitude of the signal voltage.

RESOLVERS

You have already learned something about resolvers in Fire Control Technician 3, NavPers 10173-A. As you know, a resolver is a variable transformer capable of unlimited rotation. In its most common form it consists of a stator and rotor, each wound with two separate coils placed precisely at right angles to each other. This configuration is shown in figure 2-28. The two stator windings are normally stationary, and serve in some applications as the primaries. However, they may be used as secondary windings in other types of resolvers. The rotor windings serve also as secondaries or primary windings, depending on type and application of the resolver. The rotor assembly can be rotated with respect to the stator windings. Some resolvers have separate connections for each winding; others use one common lead for the primaries and another for the secondary. The common lead is usually connected to ground. Some types have extra windings for feedback, and others leave out either one primary winding or the secondary.

Resolver Application

Resolvers are used extensively in computers, coordinate converters, in some radar sets, in weapon direction equipment, target designation equipment, and for data transmission. These devices perform electrical computations involving (1) resolution, (2) composition, and (3) combination.

Like all devices that are based on the transformer principle, a resolver is strictly and a-c device. You cannot connect a resolver directly into a d-c circuit. You do not have this problem with pots, which, since they are resistors, work equally well with alternating or direct voltage. If the input to a resolver is direct current, in many cases you can modulate an a-c voltage with the d-c signal, pass the combined signal through a resolver, and then demodulate (or rectify) the output for application to any remaining d-c component. Of course this process is not necessary if all units within the servosystem operate on alternating current. (Modulators and demodulators are explained in the next chapter.)

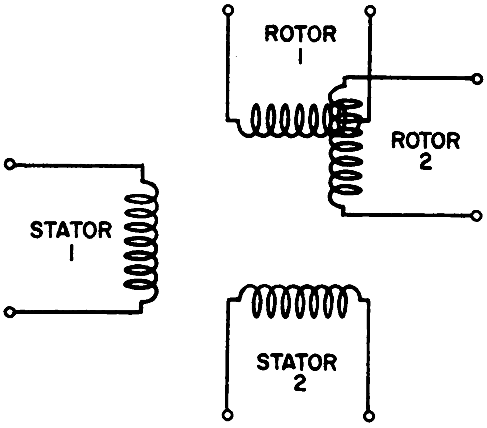


Figure 2-28.—Typical resolver diagram.

Resolver Operation

So far, it has not been explained exactly what a resolver "resolves." Briefly, if you apply an alternating voltage, labeled E in figure 2-29A, to the rotor winding (in this example the rotor has only one winding), the output voltages from the two stator windings will be sine and cosine functions respectively of the angular position (Θ) of the rotor. In other words, as shown in figure 2-29, they will be equal to E sine (Θ) and E cosine Θ. Referring to the vector triangle in part B of figure 2-29, where the vector E is drawn as the resultant or hypotenuse of the triangle, you can see that the resolver actually breaks down or resolves vector E into its two rectangular components. This process is called resolution of vectors.

You can look at vector resolution from another point of view. In the previous example a vector was given in polar coordinates. The length of the vector represents magnitude and an angle Θ direction. The resolver breaks down the vector into rectangular components. Now, in the place of the word components, you can substitute the word coordinates. This term is just as correct as components. Therefore, you can say that another function of a resolver is to convert coordinates—in this case polar to rectangular.

Still another point of view can be considered. You know from your study of trigonometry that if you are given one side of a right triangle and

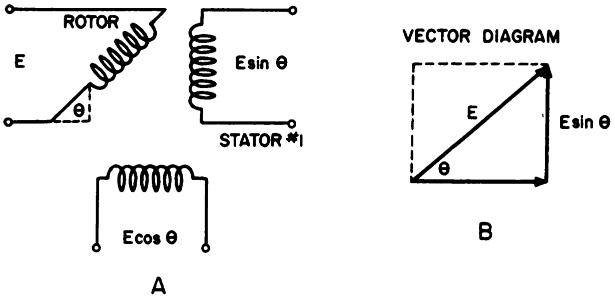


Figure 2-29.—The resolution of an a-c voltage which represents a vector. 55.28

an adjacent angle, you can find the other two sides. In our example, the resolver was given one side (E, the hypotenuse) and an adjacent angle (θ). The output of the resolver is the length of the other two sides. Thus, you can say that a resolver can solve for two unknowns in a right triangle.

Now, let's make our resolver work backwards. If you apply two in-phase voltages to the stator windings with the polarity and magnitude shown in figure 2-30A and then rotate the rotor by hand, or a servo, to the given angle, the output from the rotor will be 5 volts. The output voltage is the vector sum of the A and B voltages. This process is called composition. The geometry of the problem is shown in figure 2-30B. Again note the transformation of information from one coordinate system to another. In this case, rectangular coordinates were changed to polar coordinates.

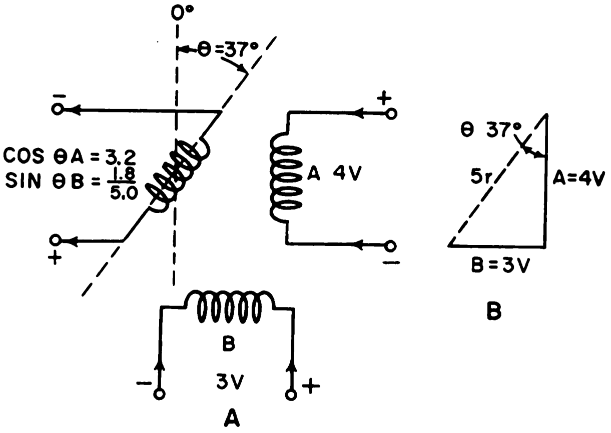


Figure 2-30.—Resolver composition. 55.29

CHAPTER 3

SERVOMECHANISM DEVICES (PART II)

In the previous chapter we discussed some of the types of sensing elements found in fire control servosystems. In this chapter we will continue our discussion of servos, and see how the servosystem utilizes the information that the sensing element provides.

AUTOMATIC SELECTING OR SYNCHRONIZING NETWORK

Use of a dual-speed synchro data transmission system increases the dynamic (moving) and static (stationary) accuracy of the servosystem. But a dual-speed synchro transmission introduces a problem—how can a servoamplifier tell when it is, or should be, receiving a fine or a coarse signal? During normal operation, the fine signal should have control of the servo. The coarse signal should be in control only when the load is far out of synchronism.

To solve this synchronization problem, a circuit is included in the servo to sense how far the load is from the desired command position, and then to switch the appropriate signal into control. There are numerous methods of automatically selecting the fine or coarse signal; they can be classified according to which signal or signals are applied to the amplifier.

In one type of automatic signal selecting (synchronizing) circuit, the coarse signal is always applied. When the error is small, this coarse signal is so small that it has practically no effect on the amplifier—the amplifier then works on the larger fine control input. When the error is large, the fine control signal is effectively shorted out, leaving the coarse control signal as the only input to the amplifier.

Another type of automatic selector has contacts which control both signals. When the error is small, the fine control contacts are closed, and the fine control signal is the only input to the amplifier. When the error is large, the coarse control contacts close, and the coarse control signal is the only input to the amplifier.

Automatic selecting circuits (many publications call them synchronizing networks) may also be classified according to the devices used in the circuit. Some of these devices are relays, diodes (both semiconductor and vacuum tube), and gas tubes (thyratron and neon).

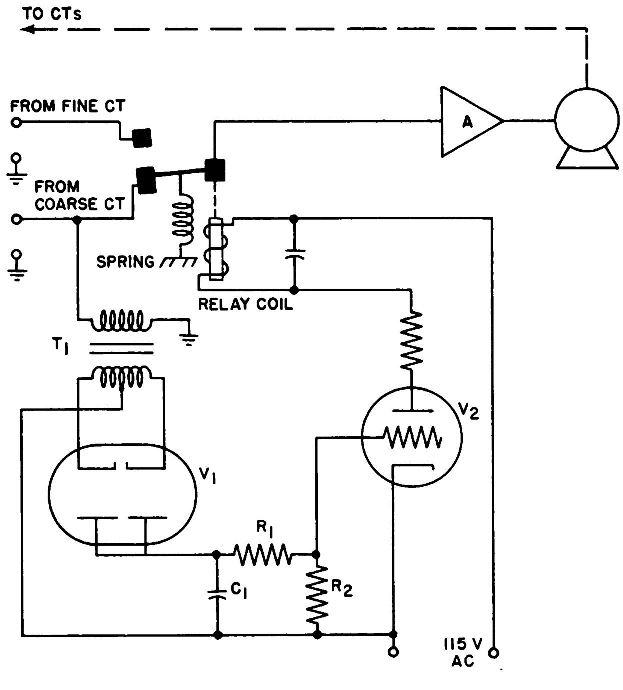
RELAY-OPERATED SYNCHRONIZING NETWORK

Figure 3-1 shows a schematic of a typical synchronizing network which uses a relay to switch the fine and coarse synchro control signal inputs to the servoamplifier. Follow the two signal paths from their control transformers to the amplifier. Notice that both signal circuits are opened and closed at the contacts controlled by the relay.

Start out by tracing the fine signal from the fine CT to the servoamplifier. The relay coil pulls the contact arm down. This closes the upper contact, and the fine signal is fed directly to the servoamplifier. You may be wondering how the relay was energized to pull the arm down.

Before you can answer that, you'll have to remember what you've learned about the operation of a triode tube. You will recall that the potential on the control grid determines whether or not the tube will pass current. With a strong negative potential on the grid, the tube has a high resistance, and very little current passes. With a weak negative potential on the grid, the tube has a low resistance, and current flows across the tube whenever the plate goes positive. The grid potential is developed across R2. It is this voltage across R2 that determines whether or not the tubes will pass current.

Now trace the coarse signal circuit. The coarse signal appears across the primary of the transformer, T1. The secondary voltage of T1 goes to V1 for full-wave rectification. The rectified output of V1 is filtered by R1-R2 and C1. Part of the rectified and filtered coarse signal is developed across R2, making the top of R2



55.30
Figure 3-1.—Relay synchronizing network.

negative. Thus the coarse signal controls the grid bias of V2.

When the coarse signal is small, the bias at R2 is small; V2 conducts current on every positive alternation of the supply voltage. This current flows out of the V2 plate, through the relay coil, and back to the source of supply. Then the relay pulls the contact arm down and closes the upper contacts. The fine signal goes to the amplifier. The capacitor in parallel with the relay keeps the relay operated during negative alternations of the supply voltage.

When the coarse signal is large, the bias at R2 is large and V2 conducts very little current. With very little current through V2, the relay coil releases the contract arm and opens the fine signal circuit. Then the spring pulls the contact arm down and closes the lower contacts. The coarse signal is then fed to the servoamplifier.

There are many variations of the circuit just described, but they all operate in much the same manner.

SELENIUM DIODE SYNCHRONIZING NETWORK

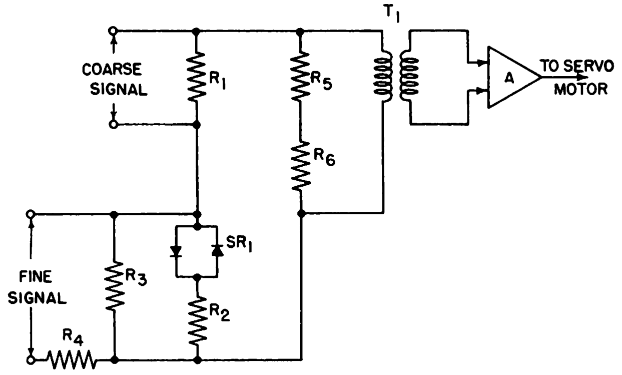


Figure 3-2.—Selenium diode synchronizing network. 55.30.0

Figure 3-2 shows a synchronizing network which uses selenium diodes (rectifiers) to perform the signal switching function. Notice that there is no contact switching arrangement. This means that both fine and coarse signals are always connected to the amplifier. It also indicates that the fine signal must be shunted away from the amplifier when a large error is present.

The coarse signal is introduced across R1, and the fine signal across SR1, R2 and R4. Notice that R1, SR1 and R2 form a parallel circuit with R5 and R6. The amplifier's input signal (from T1) is developed across R5 and R6.

First, study the circuit as it handles a small error. The fine synchro is displaced much more than the coarse synchro. This makes the fine signal much stronger than the coarse signal. Both signals appear across R5 and R6. However, the fine signal overrides the coarse signal and is the input to the amplifier. Thus when the error is small, the fine signal has control.

Now study the circuit as it handles a large error. You know that the fine signal must be shunted so that the coarse signal can take control. The selenium rectifier, SR1, does the job of shunting the fine signal. When the error is large with respect to the desired position and the load position of the servo, both the coarse and fine synchro signal voltages are large. The fine signal across SR1 exceeds its forward breakdown voltage and its resistance falls to a very low value. Most of the fine signal voltage is dropped across the series resistor, R4, with practically no voltage developed across R2 and the diodes.

The selenium diodes are the tricky part of the circuit. For a small error, the signal voltage is comparatively weak and SR1 conducts proportionately. As the signal increases, the current flow across SR1 increases until it reaches a point where the diode's resistance breaks down under the load. At this point, the voltage developed across SR1 and R2 drops to a very low value. That puts practically all the fine signal across R4. Effectively, the fine signal is shunted from the parallel circuit of R5 and R6. The coarse signal becomes the input to the amplifier.

As long as a relatively large current passes through SR1, it will remain in its shorted condition. But, when the current across it decreases, the selenium rectifiers will heal themselves and their resistance will return to its previous high value, at which time the fine signal will resume control.

The semiconductor diode synchronizing network is fairly common, so let's take a look at another circuit using this technique. This circuit is illustrated in figure 3-3. Within a range of approximately 3° on either side of the synchronizing point, the coarse signal is effectively blocked because of the high impedance of the series diodes, CR3, CR4, CR5, and CR6. With the coarse signal blocked, the fine signal is fed into the summing network and is in control of the servo. However, this signal is limited to a very low voltage by the parallel diodes, CR1 and CR2.

Both the fine and coarse voltage inputs will increase as the error in correspondence is increased. Remember that the resistance of the diode rectifier decreased with an increase in current flow across it. CR1 and CR2 develop the fine signal. A point will be reached (about 3° error) when CR1 and CR2 will be incapable of dropping a greater voltage. Any increase in current gives us a decrease in resistance and a decrease in the fine voltage output to the summing network.

Now let us look at the coarse signal. In figure 3-3 you will notice that the coarse signal is developed across R1. Also notice that the diode network of CR3, CR4, CR5, and CR6 is in series with R1. Errors in correspondence which are less than 3° will cause some current to flow across R1 and the diode network. However, this current is small and will cause the diode network's resistance to be high. Therefore most of the coarse signal voltage is dropped across the diode network and very little voltage is developed by R1. In this condition the resultant voltage in the summing network is predominantly from the fine synchro. As we get further out of synchro correspondence, the current through the coarse signal diode will increase causing a decrease in the diode network's resistance. A smaller percentage of voltage will be dropped across the diode network and thus more signal voltage developed across R1. Circuit resistance is selected so that the voltage developed across R1 (coarse signal) will override the voltage across CR1 and CR2 (fine signal) when the synchro correspondence error is 3° or more. The coarse signal now has control of the servo. When the servo error becomes less than 3°, the fine signal resumes control.

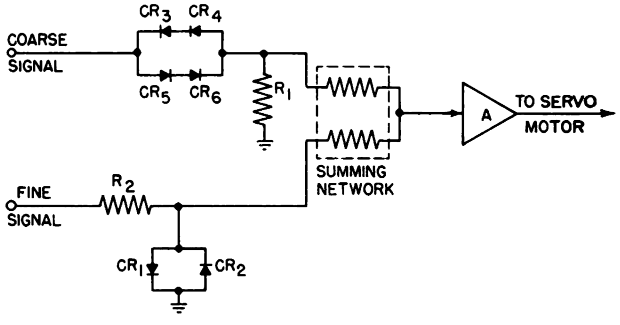


Figure 3-3.—Semiconductor diode synchronizing network. 55.31

MODULATORS

Some fire control servos use a d-c voltage as an error signal. If the servomotor is alternating current, it is obvious that the d-c error signal must be changed to alternating current before it can control the servomotor. When a d-c signal is converted to alternating current, both sense (polarity) and magnitude of the d-c signal must be contained in the output alternating current. The circuit or device that changes (converts) a d-c error voltage to alternating current is called a modulator. Modulator circuits use elements that act as synchronous switches. Examples of these elements are diodes, crystal or metallic rectifiers, triodes, transistors, and mechanical contactors. The "switches," regardless of type, are operated at a carrier frequency (the frequency of the reference voltage, usually 60 or 400 cycles/sec) and the resulting alternating current is a series of pulsating voltages with amplitudes proportional to the d-c error voltage. The phase of the a-c output corresponds to the polarity of the d-c error voltage.

VIBRATOR MODULATORS

A modulator may be either an electromechanical or an electronic circuit. An example of an electromechanical circuit, called a vibrator or chopper, is shown in figure 3-4. The coil is energized by alternating current at the appropriate frequency, usually 60 or 400 cycles per

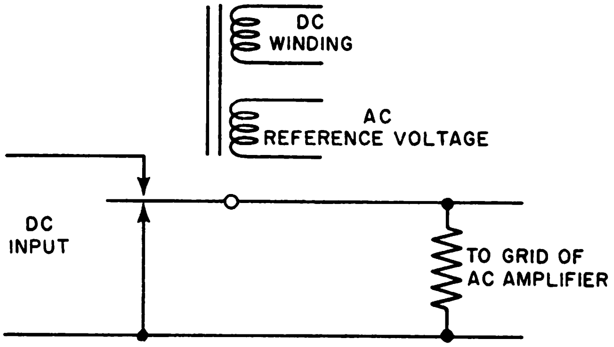


Figure 3-4.—Electromechanical vibrator (chopper). 55.32

second. To prevent the vibrating arm from being attracted twice by the coil during each cycle, some direct current is passed through the coil, or through another coil wound on the same core. Thus when the alternating current flows in the other direction, its magnetizing force is canceled by that of the direct current, and the attraction on the arm is reduced. The arm thus vibrates at the frequency of the a-c supply (reference) voltage. Most choppers use a permanent magnet in place of the d-c winding.

To reduce the power required to drive the arm, the arm is usually tuned so that it vibrates naturally at the proper frequency. The output is then a square wave, having the level of the d-c input for one-half cycle and zero level for the other.

Blocking condensers in the amplifier that follows the chopper remove the d-c component, so that the signal becomes a square wave with an amplitude proportional to the d-c signal level and a phase which reverses when the d-c signal changes polarity. This amplifier also discriminates against high frequency signals, so that the square wave ultimately is converted to a sine wave at the frequency of the vibrator switching.

CRYSTAL DIODE MODULATOR

The cyrstal diode modulator (fig. 3-5) consists of a diode bridge and transformer network. When a reference voltage is applied to transformer T1, diodes CR2 and CR3 conduct during the negative alternation of the reference voltage. (There is a 180° phase reversal in T1.) Conversely, diodes CR1 and CR4 conduct on the positive half-cycle of the reference voltage. Electron flow during the positive and negative alternations is represented by open arrows and dotted arrows, respectively. If a positive d-c signal voltage is applied during the negative-going alternation, electrons will flow from ground, through the upper half of the primary winding of transformer T2, through diode CR2 and through the upper half of the secondary winding of transformer T1 to the d-c source. Current flow through the bottom of T2, CR4, and the bottom of T1 secondary is opposed by the opposite polarity across CR4. On the positive-going alternation, electrons will flow from ground, through the lower half of the primary of transformer T2, through diode CR4, and through transformer T1 to the d-c signal source.

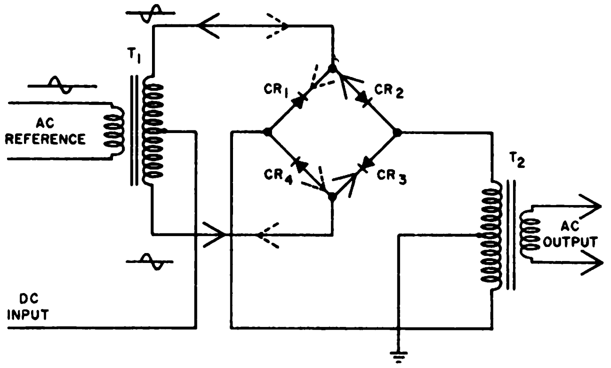


Figure 3-5.—Crystal diode modulator. 55.33

If a negative d-c signal is applied, electron flow through the circuit will be reversed. That is, electrons will flow from the d-c signal source, through diodes CR3 and CR1 in turn, to ground. Since, in all cases electrons are caused to flow through the primary of transformer T1 at the rate of the reference voltage, the output of this transformer will be at the frequency of the reference voltage. The polarity of the a-c output signal is determined at any given instant by both polarity of the d-c input and the polarity of the a-c reference voltage.

ELECTRONIC (VACUUM TUBE) MODULATORS

An example of an electronic modulator is shown in figure 3-6. The input d-c error voltage is impressed between E1 and ground. The a-c reference voltage along with the action of V1, V2, R2, and R3 effectively clamp output E2 at zero potential for one-half cycle of the reference

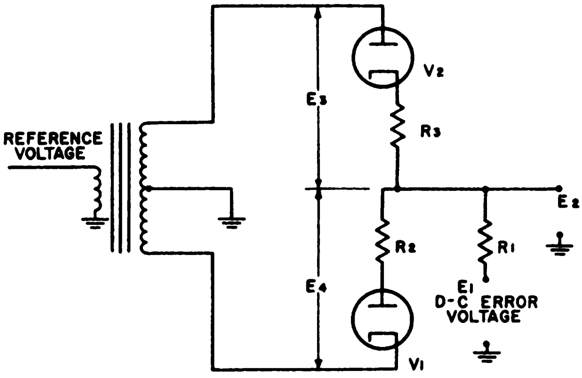


Figure 3-6.—Electronic modulator. 55.34

voltage. To accomplish this, the following conditions must exist:

1. R1 must be much larger than R2.
2. R2 and R3 are equal.
3. V1 and V2 must be matched (usually a balance circuit is included to match the tubes).

With a reference voltage applied, making the plate of V2 positive and the cathode of V1 negative, current will flow through V1, R2, R3, and V2. Since R2 equals R3, voltage E3 will equal E4.

If the d-c error voltage is positive, V1 will pass current down across R1, effectively dropping the amount of the error signal. The voltage output at E2 for this half cycle will be zero. If he d-c error voltage is negative, current will pass up across R1, R3, and through V2 to the source. R1 once again (because of its size) drops an amount almost equal to the d-c error voltage and the signal at E2 will again be almost zero.

We can readily see that when the tubes conduct, the voltage at E2 will be almost zero, and when they are cut off by the reverse polarity of he reference voltage, the output voltage will be qual to the d-c error input. This will result in pulsating d-c output with its amplitude and hase determined by the amplitude and polarity f the d-c error voltage.

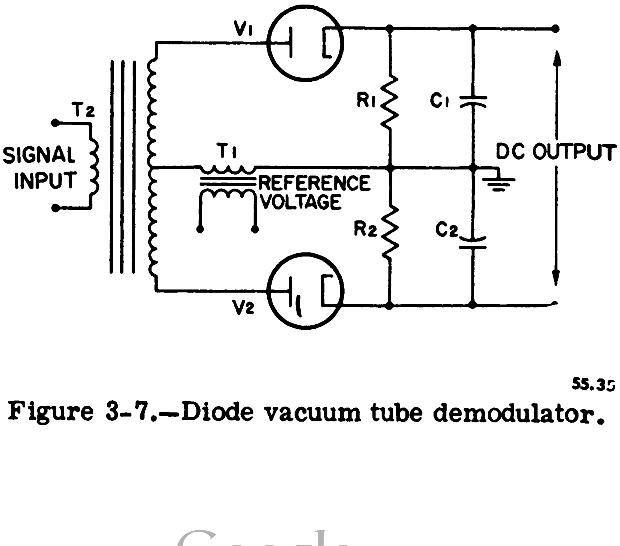
DEMODULATORS

Some fire control servos use d-c servomotors to drive a load. A typical application of -c servomotors is in antenna and director amplidyne power drives. The input signal to the ervoamplifiers in the amplidyne type of servo is usually an a-c synchro voltage. This requires that the a-c signal be converted to direct current. To accomplish this, a demodulator is used. Demodulators are often referred to as phase-sensitive rectifiers, phase-sensitive detectors, phase-discrimination converters, discriminators, or simply detectors. These are high-sounding names for, as you will see, a circuit that is fairly simple. If you understand the operating principles of modulators, demodulators will be easy for you to learn.

DIODE DEMODULATORS

A typical diode demodulator (phase detector) is shown in figure 3-7. As illustrated, an a-c supply voltage serves as the reference voltage for the detector. This voltage must come from the same source that is supplying a-c excitation to the synchro system, or whatever type of error detector is used, and must be in phase with the common supply voltage. This permits a phase-comparison of the error voltage with the reference voltage. The plates of the two diodes are supplied with this reference voltage in such a manner that the two plates will be in phase. Assuming that there is no error signal from T2 to the plates of the diodes at the time the plates are on a positive half-cycle, the two diodes will conduct equally. The voltages produced across R1 and R2 are equal, making the cathode of V1 and V2 at equal potential with respect to ground. With the two output terminals at the same potential, the output voltage will remain at zero as long as no error signal is applied.

If an error signal is applied to T2 making the plate of V1 positive at the same time the reference voltage on the plates of V1 and V2 is on its positive half-cycle, V1 conduction will be increased and V2 conduction decreased over the



55.35

Figure 3-7.—Diode vacuum tube demodulator.

no-signal condition. Since the voltages applied to the plates are both alternating, the voltage developed across R1 and R2 would also be alternating. However, R1-C1 and R2-C2 have a long time constant compared to the input frequency, and therefore filter most of the ripple, giving a d-c output.

If the error signal applied to T2 is changed by 180 degrees, V2 would now increase its conduction while the conduction of V1 would be reduced. This would result in an output voltage of reversed polarity. Variations of the diode phase detector may be encountered; however, they all depend on the same basic principles of operation.

TRIODE DEMODULATOR

The demodulator shown in figure 3-8 is a full-wave phase-sensitive demodulator. It compares and a-c signal voltage with an a-c reference voltage to produce a d-c output. In this circuit there are two sets of conditions for the polarities of the input voltages, since at any instant of time the reference voltage and the signal voltage will be in phase or 180° out of phase.

An in-phase condition is shown in figure 3-8. An examination of the existing instantaneous polarities reveals that only V1 can conduct. Each section of V1 will conduct on alternate half-cyles of input voltages. This is approximately the action of a full-wave rectifier. Refer to figure 3-8 and consider the instantaneous polarities present:

1. V2A is not conducting because its plate is negative.
2. V2B is not conducting because of the negative bias on its grid; the windings of T2 bias it below cutoff.
3. V1B is not conducting because its plate is negative.
4. V1A is conducting because both plate and grid are positive with respect to the cathode. The current, I, will flow through the tube and resistor R1 as shown, producing the output d-c voltage across R1.

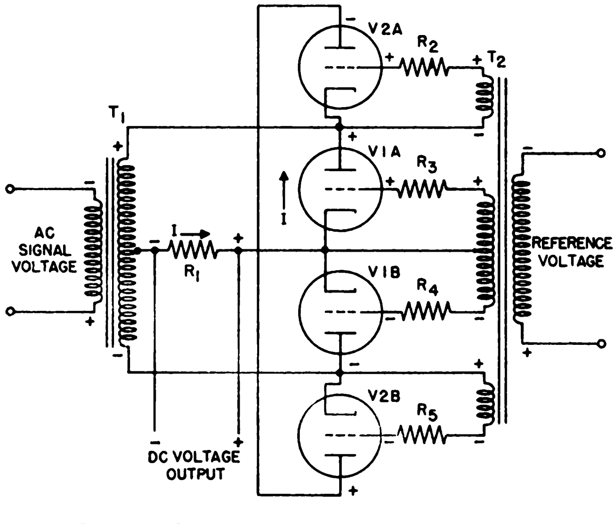


Figure 3-8.—Triode demodulator. 55.36

On the alternate half-cycle of the a-c voltages, V1B will conduct and the d-c current through R1 will be in the same direction as before.

For the reverse condition, when the a-c voltages are 180° out of phase, V2 will conduct. The d-c output voltage across R1 will reverse its polarity.

SERVOAMPLIFIER

The purpose of a servoamplifier is to control an output in a manner dictated by an input. Normally, the servosystem's signal input is at a low energy level and must be greatly increased to perform an appreciable amount of work. This is the job of the servoamplifier. The amplifier controls a large power source which is activated by a low-powered error signal. This is shown in figure 3-9A. Figure 3-9B shows a simple power control using a triode as the controlling element and a battery as the power reservoir.

There are just about as many different amplifiers as there are jobs for amplifiers to do. Each amplifier is designed to do a particular job. Each part of the amplifier is selected to do a particular part of the total job. You can't just look at a circuit and understand why everything is there. The best way to analyze an amplifier is to divide it into stages, coupling circuits, decoupling circuits, and biasing networks. In Basic Electronics, NavPers 10087-A, you have studied each of these circuits—you know what they are supposed to do.

Servoamplifiers can be broadly divided into functional stages. Previously we saw how the error signal is selected, and modulated or demodulated to suit the individual amplifier. The first stage or stages of amplification increase the voltage swing of the error signal. When the signal voltage is amplfied a sufficient amount, it is used as the input to the power stage. Here the primary concern is current delivered at a steady voltage under load conditions. The push-pull type amplifier is extensively used in fire

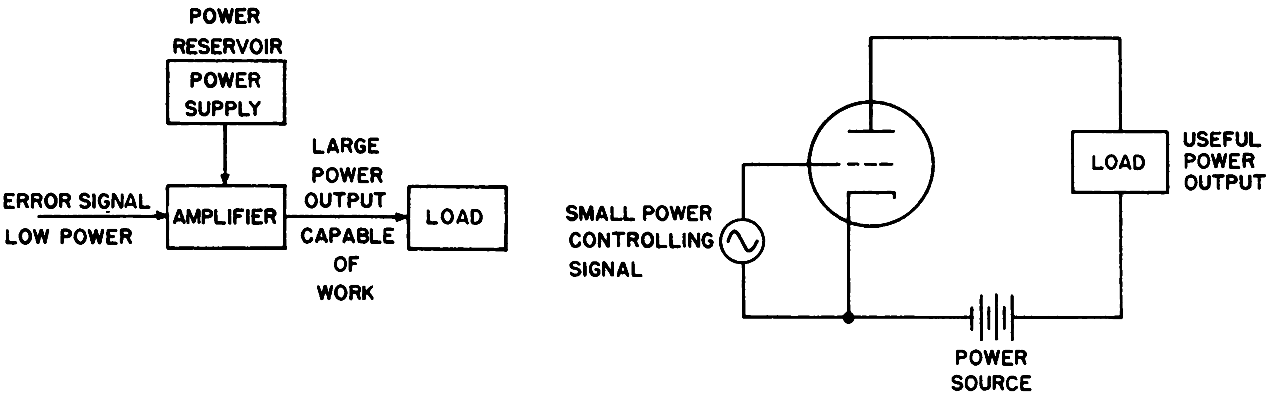


Figure 3-9.—Amplifiers job in the servo.

55.37

control servosystems. A push-pull amplifier is preceded by a phase inverter or paraphase amplifier. The power stage may be one or more stages, depending on the power output needed.

In general, the higher the gain of the amplifier, the tighter the control and the more accurate the servosystem. An increase in the system gain will reduce the system velocity errors and increase the speed of response to inputs. An increase in system gain also reduces those steady-state errors resulting from restraining torques on the servo load. However, to obtain these advantages, the servosystem must pay a price in the form of a greater tendency toward instability. A linear servosystem is said to be stable if the response of the system to any discontinuous input does not exhibit sustained or growing oscillations. The highest gain that can be used is limited by consideration of stability.

GAIN, PHASE, AND BALANCE ADJUSTMENTS

In many servosystems the gain of the amplifier can be varied by an adjustment. The gain adjustment governs the amplitude or amount of the signal voltage applied to the amplifier or one of its stages. Normally, the highest gain possible, with the servosystem possessing a satisfactory degree of stability, is the most desirable.

In a-c servosystems another adjustment which can control the sensitivity of the system is the phase adjustment. The phase adjustment is used to shift the phase relationship between the signal voltage and a reference voltage. In an amplifier with phase shift control the grid signal is shifted in phase with reference to the plate voltage of a tube. The tube's firing point is delayed or advanced depending upon the phase shift of the grid signal. The phase shift can vary the firing time of the tube over the plate's entire positive alternation.

A phase control is included in some servosystems using a-c motors. The two windings of the a-c servomotor should be energized by a-c voltages that are 90° apart. This phase adjustment is included in the system to compensate for any phase shift in the amplifier circuit. The adjustment may be located in the control amplifier, or, in the case of a split-phase motor, it may be in the uncontrolled winding.

Servosystems using push-pull amplifiers must be balanced so that when there is no signal input to the amplifier, its output will be zero, and the servomotor will stand still with no creep. The push-pull amplifier must ensure equal torque in both directions of the servomotor.

Gain, phase, and balance adjustments are often present in one amplifier. These adjustments tend to interact, so that when one of them is changed it may affect the others. Therefore, after making any one adjustment it is a good practice to check the other adjustments.

MAGNETIC AMPLIFIERS USED AS SERVOCONTROL AMPLIFIERS

A somewhat different type of servoamplifier used in fire control equipment is the magnetic amplifier. Since magnetic amplifiers were discussed in detail in, Fire Control Technician 3, NavPers 10173-A, only their application as servoamplifiers will be covered here.

The servomotor used in conjunction with the magnetic amplifier shown in figure 3-10 is an

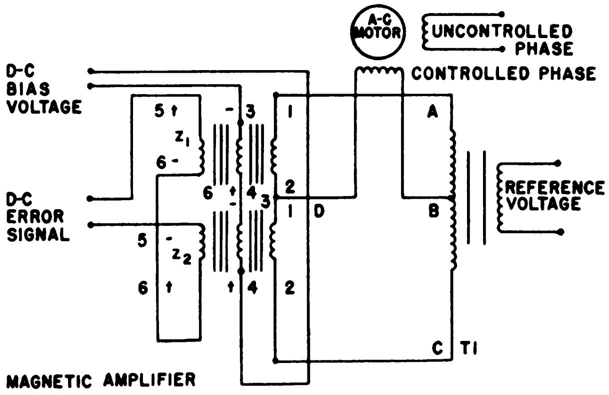


Figure 3-10.—Magnetic servoamplifier. 55.38

a-c type. The uncontrolled phase may be connected in parallel with transformer T1 by utilizing a phase-shifting capacitor, or it may be connected to a different phase of a multiphase system. The controlled phase is energized by the magnetic amplifier, and its phase relationship is determined by the polarity of the d-c error voltage.

The magnetic amplifier consists of a transformer (T1) and two saturable reactors, each having three windings. Notice that the d-c bias current flows through a winding of each reactor and the windings are connected in series-aiding. This bias current is supplied by a d-c bias power source. The d-c error current also flows through a winding in each reactor, however these windings are connected in series-opposing.

The reactors, Z1 and Z2, are equally and partially saturated by the d-c bias current when no d-c error signal is applied. The reactance of Z1 and Z2 is now equal, resulting in points B and D being at equal potential. There is no current flow through the controlled phase winding.

If an error signal is applied, causing the current to further saturate Z2, the reactance of its a-c winding is decreased. This current through Z1 will tend to cancel the effect of the d-c bias current and increase the reactance of its a-c winding. Within the operating limits of the circuit, the change in reactance is proportional to the amplitude of the error signal. Hence, point D is now effectively connected to point C, causing motor rotation. Reversing the polarity of the error signal will cause the direction of rotation to reverse.

The basic magnetic servoamplifier discussed above has a response delay equal to approximately 6 to 20 cycles. In some applications this delay would be excessive, creating too much error. However, this delay can be reduced to about one cycle by using special push-pull circuits.

STABILIZATION OR DAMPING

Fire control requires a servosystem to operate smoothly, rapidly, and with as few errors as possible. To obtain these operational characteristics, one quality is counterbalanced against the other. To increase the rapidity of response of the system to a signal, the gain is increased. This also tends to reduce error in the system. But a high gain or "tight" servo has a tendency to overshoot and oscillate, or, in other words, to be unstable.

To obtain smoothness of operations, the system's gain is damped. Damping can be obtained by either introducing a voltage in opposition to the signal voltage or by placing a physical restraint on the servo output. The function of damping is to reduce the amplitude and duration of the oscillations that may exist in the system.

DEGREE OF DAMPING

The degree of damping is determined by the required operating characteristics of the servosystem. If the system is OVERDAMPED, it will not oscillate about the correspondence point. However, due to the large amount of restraint placed on the servo, it will have a comparatively large dead-space or steady-state error. The overdamped servo will also take an excessively long time to synchronize.

On the other hand, the UNDERDAMPED servosystem will have instant response to an error signal. But it will have erratic operation due to the low amount of restraining force placed on the servo, and will oscillate or hunt about this point of synchronism. Somewhere between these two extremes, we can obtain adequate accuracy and smoothness plus a moderately short synchronizing time.

TYPES OF DAMPING

Before we consider the more common methods of damping. let us review Newton's first law of motion. This law is a statement of a property of matter—the property of inertia. Inertia is the basic cause of oscillations in a servosystem.

Newton's first law states: "A body at rest remains at rest, and a body in motion tends to remain in uniform motion in a straight line, unless acted upon by some outside force." This law tells us that whenever there are unequal forces on a body, the body must move. After we have that body in motion it will stay in motion at a constant velocity as long as there is no force present to change that motion.

As discussed previously, the servomotor must be capable of developing sufficient torque and power to position the load in a minimum of time. The servomotor and its connected load will have sufficient inertia to drive the load past the point of correspondence. This overshooting will result in an opposite error voltage, reversing the direction of rotation of the servomotor and the load. Ther servomotor will again attempt to correct the error and again overshoot the point of correspondence, with each reversal requiring less correction until the system is in correspondence. The time required for the oscillations to die out will determine the transient response of the system; it can be greatly reduced by the use of damping.

Viscous Damping

The simplest form of damping is viscous damping. This is the application of friction to the output shaft or load that is proportional to the output velocity. The amount of friction applied to the system is critical, and will materially affect the results of the system. The application of friction absorbs power from the motor, and this power is dissipated in the form of heat.

A pure viscous damper would absorb an excessive amount of power from the system. Howver, a system having some of the characteristics of a viscous damper, but with somewhat less power loss, is used in actual practice. The first damper of this type to be discussed utilizes a friction clutch to couple a weighted flywheel to the output drive shaft. A flywheel has the property of inertia.

FRICTION CLUTCH.—As the servomotor rotates, the clutch will couple a definite amount of this motion to the flywheel. The flywheel will gradually overcome its inertia and gain speed until it approaches the velocity of the motor. The flywheel in turning absorbs energy (power) from the servomotor. The amount of energy stored in the flywheel is determined by its velocity. Because of inertia, the flywheel will resist any attempt to change its velocity.

As the point of correspondence is neared and the error signal is reduced, the motor starts to slow down. The flywheel immediately releases some of its energy into the output shaft in an attempt to continue at the same speed. Thus the flywheel will cause a large first overtravel. The servosystem, to correct for this overtravel, reverses the direction of the motor. Once again the flywheel resists the motor movement and absorbs energy from the system. This drastically reduces the second overtravel and all subsequent overtravels of the motor. This effect dampens the oscillations about the point of correspondence and reduces the servosystem's synchronizing time.

The motor rotation is transmitted to the flywheel through the friction clutch. The inertia of the flywheel is an additional load on the motor. The friction clutch will slip with any rapid change of direction or speed. This slipping effectively disconnects the flywheel instantaneously, and thus governs the amount of power the flywheel will draw from the motor.

MAGNETIC CLUTCH.—Another type of viscous damper is the MAGNETIC or EDDY CURRENT damper. The magnetic damper is functionally similar to the friction clutch damper. The principal difference between the two is in the method of coupling the flywheel (inertia weight) to the servomotor output shaft. In the magnetic damper, the shaft and flywheel are coupled by a magnetic field, rather than a frictional contact. The coupling is made by the interaction of a magnetic field generated by a permanent magnet which rotates with the rotor of the servomotor and the induced eddy current in the flywheel.

The effect of viscous damping is shown in figure 3-11. The solid line shows the action of the load without damping. The time required to reach a steady-state condition should be noted. This time is greatly reduced with damping, although the initial overshoot is increased. Viscous dampers effectively reduce transient oscillations, but they also produce an undesirable steady-state error (velocity lag or position error). Since the friction damper absorbs power from the system, its use is normally limited to small servomechanisms.

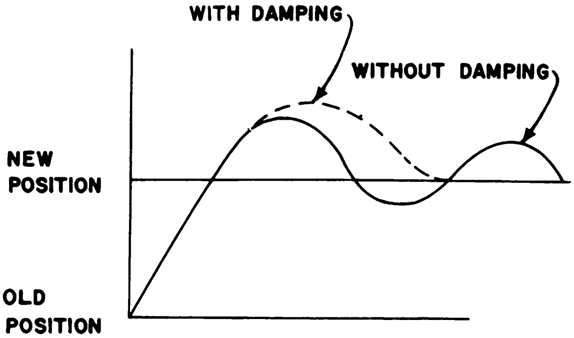


Figure 3-11.—Effect of friction damper. 55.38.0

Error-Rate Damping

Since no physical device can respond instantaneously to a sudden force, there is a time lag between the signal input of a servosystem and its output response. To reduce this time lag, amplification is increased. We know that this also accentuates the tendency of the system toward instability. Viscous dampers act as part of the servo load, so they are not the answer to reducing the response lag. The answer lies in increased amplification with error-rate damping.

Error-rate damping consists of introducing a voltage that is proportional to the rate of change of the error signal. This voltage is combined with the error signal in the proper ratio to obtain optimum servo operation with negligible overshooting and oscillations.

The advantages of error-rate damping are:

1. Maximum damping occurs when a maximum rate of change of error signal is present. This normally would occur when the servo load reverses direction. Obviously, this is when maximum damping action is required.
2. Since a CHANGE in the signal causes damping, there is a minimum amount of damping when no signal, or a signal of constant strength, is present. This means small steady-state errors.

There are two methods of generating an error-rate voltage normally found in fire control equipment. They are mechanical devices and electrical networks. First we will discuss the mechanical devices which provide an error-rate damping voltage.

ERROR-RATE DAMPING DEVICES.—A widely used method of generating an error-rate voltage employs a tachometer generator, commonly called a "tach." This device is mechanically coupled to, and rotates with, the servomotor's output shaft. The tach's output is a voltage which is proportional to the speed of the servomotor.

A-C Tachometer Generators.—Figure 3-12 shows schematically one type of a-c tach generator used in many computing and positioning servos. The output of this tach is a voltage whose amplitude is proportional to the speed, and whose phase is determined by the direction of its rotor. The unit the speed and direction of its rotor. The unit consists of two stator windings, electrically 90° apart, and a squirrel cage rotor. One stator winding, called the primary (or reference) winding, is energized from an a-c source. The other stator winding is the generator's secondary (or output) winding. The voltage applied to the primary winding induces a magnetic field in the rotor. If the rotor is stationary, the magnetic field in the rotor is at right angles to the output winding; thus there is no output voltages.

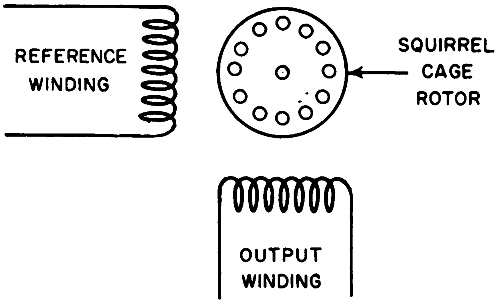


Figure 3-12.—Squirrel cage rotor tachometer generator. 55.39

When the servomotor drives the rotor of the tach, it disturbs the magnetic field so that it is no longer 90 electrical degrees from the output winding. The direction the field will move is determined by the direction of rotor motion. The amount the field will be disturbed is determined by the velocity of rotor motion. The phase of the output voltage is determined by the direction of rotor motion and the phase of the reference voltage. The amount of output voltage is determined by the speed of the rotor.

Drag-Cup Rate Generator.—Another type of a-c tachometer or rate generator which has common application in servos is the drag-cup generator. Its stator is similar to the induction rate generator previous described. The two stator windings are wound 90° apart as in the induction generator. But, unlike the induction rate generator which uses a squirrel cage rotor, the drag-cup generator has an aluminum or copper cup rotor. The rotor rotates around a stationary soft-iron magnetic core. Figure 3-13 shows the construction and operating principle of the a-c drag-cup generator. It, too, works on the principle of induction as you can see in the diagrams. As the rotor turns, it distorts the magnetic field set up by the reference (primary) winding. Flux linkage is created with the output winding. This flux linkage induces a voltage in the output winding which is proportional in amplitude to the angular velocity (rate) of the rotor and with the same frequency as the voltage applied to the primary. When the rotor turns in one direction, the output voltage leads the primary voltage by 90 degrees. But for the opposite direction of rotation, the output voltage lags the primary voltage by 90 degrees.

The frequency of the output voltage is the same as the frequency of the reference voltage. This is reasonable since the magnetic field produced by the primary winding fluctuates at the supply frequency. The output voltage is generated by the alternating flux field cutting the secondary winding; therefore, the output voltage must have the same frequency as the supply voltage.

D-C Tachometer Generators.—The d-c tachometer generator employs the same principles of magnetic coupling between the reference winding and the output winding as the a-c tach. However, the d-c tach has a stationary primary magnetic field. This magnetic field is frequently supplied by permanent magnets built into the tach. The amount of voltage induced in the rotor winding is proportional to the magnetic flux lines the winding cuts. The polarity of the output voltage is determined by the direction in which the rotor cuts the lines of magnetic flux.

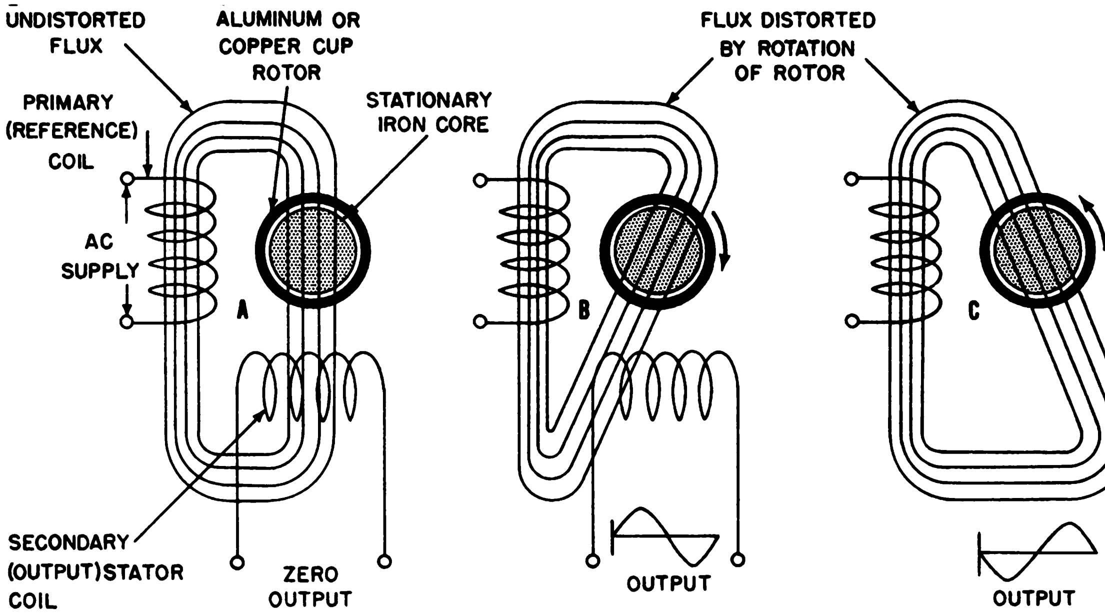
Thus both a-c and d-c tachs output voltages are indicative of both the speed (degrees per second) and direction (clockwise or counterclockwise) of the servo movement. The voltage is fed to an electrical network where it is modified so that it is proportional to a CHANGE in input voltage. This modified voltage is fed back to the servoamplifier and added to the error signal as a form of feedback. Do not confuse the error-rate voltage with the system's response loop. The damping voltage is used for stabilization, and is separate and independent of response. In the chapter on maintenance in this course, we will cover damping (feedback) adjustments.

ELECTRICAL ERROR-RATE VOLTAGE NETWORKS.—Electrical networks used for error-rate damping consist of a combination of resistors and capacitors forming an RC differentiating network. From your study of radar special circuits, you know that a differentiating circuit produces an output voltage that is proportional to the rate of change of the input voltage. In an RC circuit, if the voltage across the resistor is used as the output, it is referred to as a DIFFERENTIATOR (fig. 3-14), and, if the voltage across the capacitor is the output, it is referred to as an INTEGRATOR (fig. 3-15).

These RC networks, sometimes referred to as phase advance or lead networks, vary in design, depending on the type of error signal. Here we will use an integrator circuit or, as it is called, an integral control, as an example of this type of error-rate damping.

Integral Control.—Servomechanisms used in fire control are sometimes required to follow an input function, the magnitude of which changes at a constant rate with time, such as a direction system tracking a target. Thus, if the input is the angle of a shaft, the velocity of the shaft may be constant for a substantial percentage of time. The servomechanism may be required to respond to this type of input with substantially zero error. The error that characterizes the servo response to a constant velocity input is known as the VELOCITY ERROR.

To correct for velocity error or an inaccuracy due to a steady-state error, an INTEGRAL CONTROL may be used. This control modifies the error voltage in such a manner that the signal fed to the servocontrol amplifier is a function of both the amplitude and time duration of the error signal. This is accomplished by the use of a variable voltage divider whose output would increase with time for a constant input. As in all voltage dividers, the output is only a portion of the input which effectively reduces the amplitude of the error signal. To compensate



A. Rotor stationary
B. Rotor turning clockwise
C. Rotor turning counterclockwise

Figure 3-13.—A-c drag-cup rate generator.

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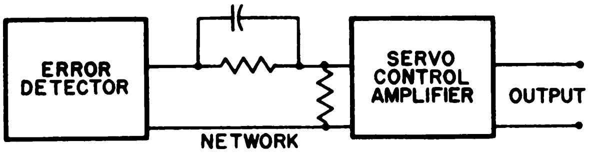

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Figure 3-14.—Error-rate stabilization network.

for this loss of amplitude, additional amplification must be used either in the form of a preamplifier or a higher gain servocontrol amplifier. With the overall gain of the system now increased to give a normal output for transient error signals, small velocity or steady-state error signals of long duration will result in somewhat increased output to the servomotor due to the action of the integral control.

The integral control, shown in figure 3-15, consists of a combination of resistors and capacitors connected to make an integrator circuit for a d-c error signal. The size of the components is such that the capacitor voltage will not have sufficient time to change with transient fluctuations in error voltage. Only that portion of the transient error signal developed across R1 will be impressed on the amplifier. However, with a velocity error or steady-state error of longer duration, the capacitor (C1) will charge, increasing the amplitude of the amplifier input.

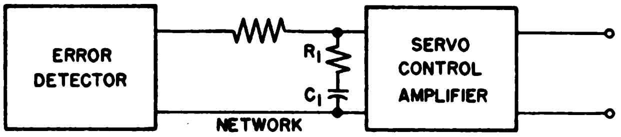

Figure 3-15.—Integrator used as an integral stabilization network.

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The network shown in figure 3-15 is not limited to d-c systems, as a demodulator may be used prior to the integrator and its output modulated for easier amplification.

SERVOMOTORS

In fire control, servo electric motors are primarily used to drive the load. The type of electric motor used within a particular equipment is determined by such factors as type of power available, output power required, speed range, inertia, and electrical noise.

ALTERNATING-CURRENT MOTORS

Alternating-current motors are frequently used in low power servo applications because of their simplicity, reliability, absence of commutator sparking, and rapid response. However, they have the disadvantage of having a narrow speed range characteristic. The theory of operation of a-c motors is discussed in Basic Electricity, NavPers 10086-A. This section will briefly discuss the types of motors applicable to servosystems.

The TWO-PHASE INDUCTION MOTOR is a widely used a-c servomotor. The stator of the motor consists of two similar windings which are positioned at right angles to each other. The rotor may be wound with short-circuited turns of wire or it may be a squirrel cage rotor. The squirrel cage rotor is most common; it is made up of heavy conducting bars which are set into armature slots, the bars being shorted by conducting rings at the ends.

Two a-c voltages 90° out of phase must be applied to the stator windings in order for the motor to turn. These out-of-phase voltages generate a rotating magnetic field which induces a voltage in the rotor. This induces voltage generates a magnetic field in the rotor that is displaced 90° from the stator magnetic field. The interaction of these two magnetic fields causes the armature to rotate.

As stated previously, the voltage to the two stator windings must be 90° out of phase to cause the rotor to turn. The direction of rotation is determined by the phase relationship of the stator windings, which, in turn, is determined by the servo error detector. One phase is connected directly to one of the stator windings, while the other phase is used to energize an error detector. The resulting error voltage will either be in phase or 180° out of phase with the signal applied to the error detector. This will cause the controlled phase to either lead or lag the uncontrolled phase by 90 degrees.

Most induction motors have low starting torque and high torque at high speed. For servo applications, it is desirable to have high starting torque in order that the system may have a low time lag. This may be accomplished by increasing the armature resistance with the use of materials such as zinc for the conducting bars. This increased torque at low speed results in decreased torque at high speed. However, increased stability of the servosystem is a desirable result of this change.

SPLIT-PHASE A-C MOTORS are similar to the two-phase induction motors. They differ only in that a phase-shifting network is used to shift the phase of the voltage supplied to one of the windings by 90 degrees. This is usually accomplished by connecting a capacitor in series with the uncontrolled winding of the stator. Direction of rotation and reversal is accomplished in the same manner as in the two-phase induction motor discussed above.

Other types of motors that may be used with an a-c power supply are SHADED POLE, UNIVERSAL, and REPULSION motors. They utilize various methods of obtaining rotation reversal. However, they are seldom found in fire control equipments.

DIRECT-CURRENT MOTORS

Direct-current motors have an advantage of having higher starting and reversing torque, and less weight for equal power, than a-c motors.

SERIES MOTORS are characterized by their high starting torque and poor speed regulation with a change in torque. Higher torque can be obtained on reversal of direction with a series motor than any other type. However, it is a unidirectional motor and requires special switching circuits to obtain bidirectional characteristics. This is normally done by switching the armature or field connections, but not both.

A variation of the series motor that has bidirectional characteristics is the SPLIT-SERIES MOTOR. The motor has two field windings on its frame, only one of which is used for each direction of rotation. This reduces the number of relay contacts required for reversing by one-half. This double winding also reduces the torque capabilities of the motor as compared to a straight-series motor wound on the same frame.

The most frequently used d-c servomotor is the SHUNT MOTOR. Its direction of motion is controlled by varying the direction of flow of either the armature or field current. The uncontrolled current is usually maintained constant to preserve a linear relationship between the motor output torque and the voltage or current input. The field windings are usually two differentially wound coils to facilitate direction control of the field current by the servocontrol amplifier. The field current is usually controlled with vacuum tubes or thyratrons.

ACCELEROMETERS

An accelerometer may be defined as a device which gives an indication, usually in the form of a voltage, proportional to the acceleration to which it is subjected. The operation of an accelerometer is based on the property of inertia (Newton's first law of motion). A simple demonstration of inertia happens to us almost every day. You know that if your automobile is subjected to acceleration in a forward direction, you are forced back in the seat. If your auto comes to a sudden stop, you are thrown forward. When your auto goes into a turn, you tend to be forced away from the direction of the turn—that is, if your auto turns left, you are forced to the right, and vice versa.

In figure 3-16, we replace the human in an auto with a mass suspended in an elastic mounting system. Any acceleration of the auto will cause movement of the mass relative to the auto. The amount of displacement is proportional to the force causing the acceleration. The direction in which the mass moves in relation to the auto is opposite to the direction of the acceleration.

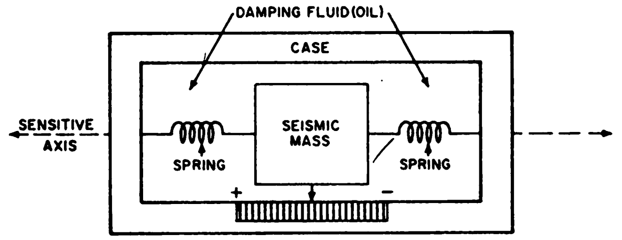

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Figure 3-16.—Simplified linear acclerometer.

The movement of the mass is in accordance with Newton's second law of motion which states that when a body is acted on by a force, its resulting acceleration is proportional to the force and inversely proportional to the mass of the body. In mathematical terms this may be expressed as: $a = \frac{E}{M}$, or by transposition: $F = Ma$, where F equals force, M equals mass, and a equals acceleration.

When no acceleration is present, the mass in the figure will be at rest. When acceleration is present, the mass will lag in proportion to the acceleration force. In other words, the car moves but the mass wants to remain at rest. Now that you understand the basic physical principles involved, let's take a close look at a simple linear accelerometer.

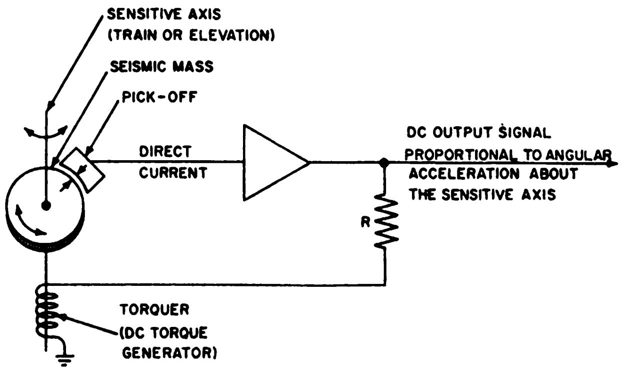
LINEAR ACCELEROMETER

Figure 3-16 is a simplified drawing of a linear accelerometer. It consists of a mass, called the inertial mass, seismic mass, or proof mass, which is free to slide along the sensitive axis within the case. The movement of the mass is limited by the springs. When the case is accelerated, the seismic mass, because of its inertia, tends to remain stationary. This results in a relative movement of the mass with respect to the case. When the stretch of the springs overcomes the inertia of the mass, the springs cause the mass to stop moving with respect to the case. The displacement of the mass with respect to the case is directly proportional to the acceleration of the case. When the case stops accelerating, the springs return the mass to its zero position (the reference position). To keep the springs from causing the mass to overshoot and oscillate about the reference position, some form of damping is needed. This is usually supplied by using an oil-filled case with vanes for oil to bypass the mass.

Accelerometers are sensitive to gravity when their sensing axis is positioned so that gravity can move or attempt to move the seismic mass. This is useful in that we can use gravity as a reference for calibration, but it can be a serious problem because of the errors it may cause in acceleration measurements. If the unit is placed with the sensing axis vertical, the mass will be displaced such that the output is one G, or one gravity. This is done for calibration; then when the sensitive axis is turned so that it is horizontal to the earth, the springs center the mass, and the output of the unit is zero.

ANGULAR ACCELEROMETER

The basic angular accelerometer shown in figure 3-17 works on the same principle as the


SENSITIVE AXIS (TRAIN OR ELEVATION)
SEISMIC MASS
PICK-OFF
DIRECT CURRENT
DC OUTPUT SIGNAL PROPORTIONAL TO ANGULAR ACCELERATION ABOUT THE SENSITIVE AXIS
R
TORQUER (DC TORQUE GENERATOR)

55.44

Figure 3-17.—Simplified angular accelerometer.

linear accelerometer previously described. The two types differ in one respect—the angular accelerometer can be considered as a small servo or closed-loop system, whereas the linear accelerometer is of an open-loop nature.

The angular accelerometer consists of a mass, pickoff, damping fluid, torquer, and an amplifier. All of these elements are usually packaged as a unit.

Briefly, this is how the device works. When the vehicle (missile) or structure (director) in which the accelerometer is placed, experiences an angular acceleration about the accelerometer's sensitive axis, the mass develops a displacement. The position of the mass is measured by the pickoff. The pickoff can be precision pit, E-transformer, or any sensitive position-measuring device. In any case, the output voltage from the pickoff is proportional to angular acceleration. This voltage is amplified by a high gain amplifier whose output is a current proportional to acceleration. This current is applied to the torquer to force the mass back to its original position and thus cancel the signal. This movement is proportional to the angular acceleration experienced by the system.

APPLICATION OF A VELOCITY SERVO

It was mentioned previously that one of the most common applications of servos is for director or antenna positioning. As you know, once the radar acquires a target, it is necessary for the director (antenna) to be constantly positioned so that the tracking beam will stay on the target. This can be accomplished with servos in one of two ways—(1) by using positioning servos, or (2) by using velocity servos. Positioning servos were used in the earlier directors. But in more recent years velocity servos have been employed to keep the director on target.

Figure 3-18 shows a simplified block diagram of a typical director train servo. The elevation system is almost identical. As you look at the diagram, you will notice that there are two types of order signals—position and velocity. The velocity order signal is of interest here, but the purpose of the position signal should be mentioned briefly to give you a better picture of how this two-channel servo functions.

The director positioning servo signal is present only when the fire control system is in a designation mode. During normal target tracking, only the velocity signal is an input to the servo loop. The position signal is an a-c voltage, as is the velocity signal, and both follow a common signal path through the servosystem elements.

VELOCITY SERVO OPERATION

Director angular velocity signals which are proportional to the angular velocity of the line of sight are generated in the fire control computer. These velocity voltages are then transmitted to the director's servoamplifier. Here they are used to control the director in train and elevation. If the rate voltages have been computed correctly, the director will move at the necessary angular velocity to keep it aligned with the target. If the target changes course and speed, thus moving out of the radar tracking beam, traverse and elevation (angle) errors will be generated in the radar, and applied to the computer. These errors will determine a new set of angular rates which will enable the director to "catch up" with the target. The velocity order signals provide only one input to the error detector. In any servo, another signal must be present at the error detector. This signal is, of course, the response or answering signal which indicates what the load is doing.

The traverse velocity response signal is the other signal applied to the adding network (error detector). This signal is generated by the traverse rate gyro. The signal output of the rate gyro is proportional to the angular velocity at which the director line of sight is moving in the traverse (slant) plane.

In normal target tracking, only the traverse velocity order signal and the traverse director velocity response signal are inputs to the adding network. The phase relationship of these signals is such that the output of the adding network is equal to their difference.

When tracking a target having a constant traverse angular velocity, the output of the adding network is just large enough to drive the director at this velocity. This signal is very small during constant velocity tracking, but can be very large during acceleration and deceleration.

The a-c output of the adding network is amplified by the a-c amplifier, and is then sent to the secant potentiometer. The slider of this pot is positioned by director elevation.

The need for the secant pot is apparent when you consider that the traverse velocity and traverse velocity response are both measured in

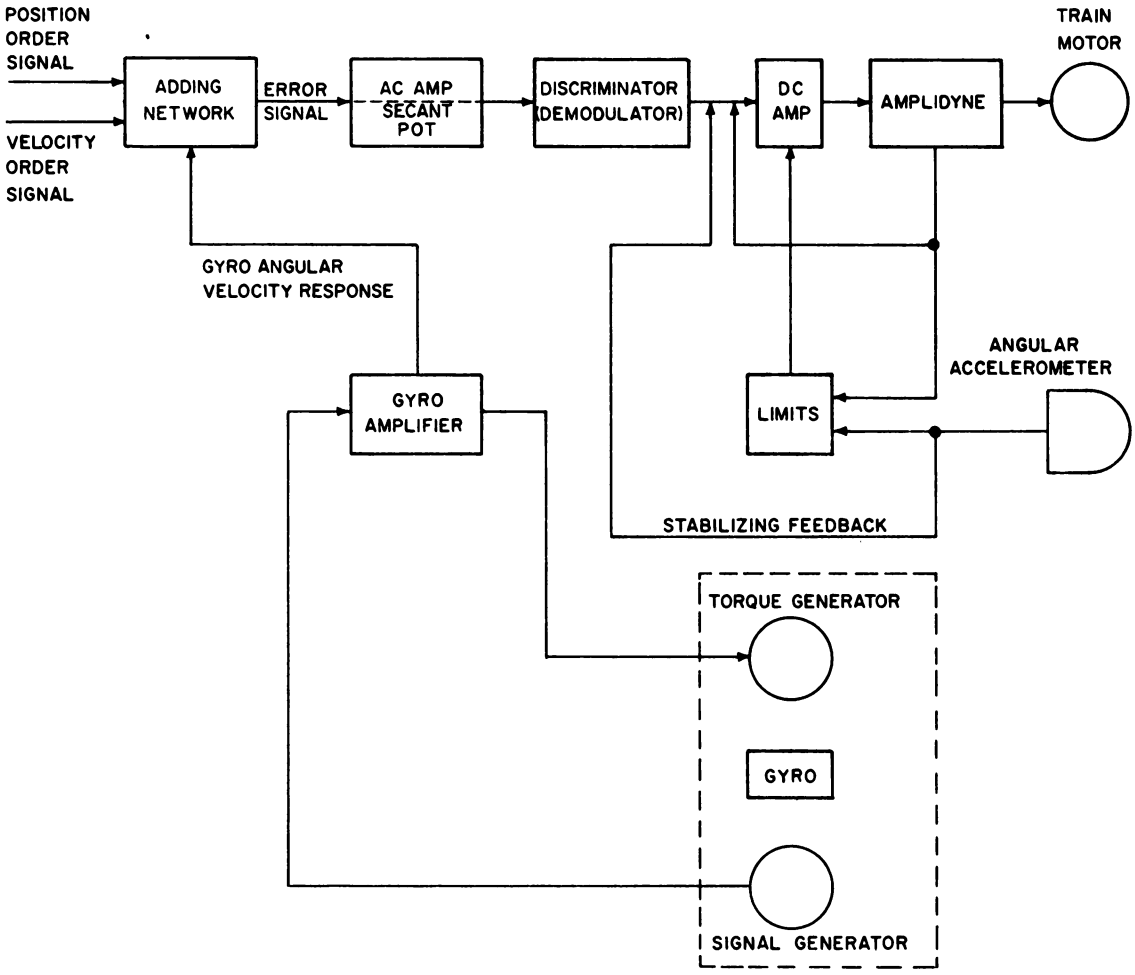


Figure 3-18.—Typical velocity servo. 55.45

the slant plane of the director line of sight. But the director turns about an axis perpendicular to the deck plane. The secant potentiometer modifies the traverse signal by a function of elevation, and thereby corrects traverse velocity measure in the slant plane to train velocity measured in the deck plane. This action provides the director with the proper value of train velocity to cause the line of sight to move at the proper traverse velocity. The technique of placing a secant pot in the traverse servosystem is fairly common, and wherever they are used in tracking loops, they perform the function described above. Note also that servo damping is provided by an angular accelerometer.

CHAPTER 4

AMPLIDYNE CONTROL CIRCUITS, GUN DIRECTOR MK 37

The amplidyne followup systems of Gun Director Mk 37 will be used in this course to explain an amplidyne control system. There are a number of other amplidyne drives with control circuits of their own, similar in characteristics but different in design. It should be noted, however, that all amplidyne control circuits operate in about the same way. Therefore, if you understand a basic amplidyne drive, it will help you to understand any amplidyne drive.

BASIC AMPLIDYNE DRIVE

An amplidyne drive is a servosystem that uses both a conventional electronic amplifier and a rotary amplifier (amplidyne generator) to supply controlled power to position heavy loads. Figure 4-1 shows a typical amplidyne drive. Notice the similarity between this diagram and that of a basic servo in figure 2-1. We can apply the nomenclature used in chapter 2 to the units shown in figure 4-1. For example, the synchro generator is the order device, and the synchro control transformer is the comparison device.

AMPLIFIER

The amplifier in the diagram rectifies and amplifies the a-c error signal. The output stage of the amplifier is arranged in push-pull. Thus the output of the amplifier is two opposing d-c currents. This furnishes the control currents for the amplidyne generator. The amplidyne generator is the rotary amplifier of the power drive. This is the instrument which amplifies a low-powered signal into one strong enough to drive the director. If the principles of d-c generators (particularly armature reaction) and amplidyne generators are hazy in your mind, review Basic Electricity, NavPers 10086-A.

AMPLIDYNE GENERATOR

Figure 4-2 is a simplified schematic diagram of the amplidyne generator, the drive motors, and their associated circuits. A conventional a-c induction motor drives the generator. The generator is rotated in one direction, and at a constant speed. The generator excitation is supplied by the control windings F1-F2 and F3-F4. The control windings are energized by the opposing d-c currents from the amplifier. These windings create a magnetic field which is the resultant of both currents. With a zero error signal to the amplifier, the d-c outputs are equal and opposite. Therefore they cancel, and no control field is present in the generator. When there is an error signal to the amplifier, one or the other of the d-c currents will increase while the other will decrease a like amount, and a resultant magnetic control field will be present in the generator.

The control field causes a relatively large current in the armature winding shorted by the brushes. This armature current creates a strong quadrature field. The unshorted armature windings cut the quadrature field causing a large current in the windings. This current is delivered to the load by the load brushes.

The magnitude of the generator output is determined by the strength of the control field. The polarity of the generator output is determined by the polarity of the control field. Thus both the magnitude and polarity of the generator output are determined by the d-c current inputs from the amplifier. Later in the chapter we will see how the amplifier determines from the a-c error signal which d-c output should be the stronger.

The compensating winding in the generator is used to compensate for armature reaction. Armature reaction is caused by the magnetic field created by the current delivered to the

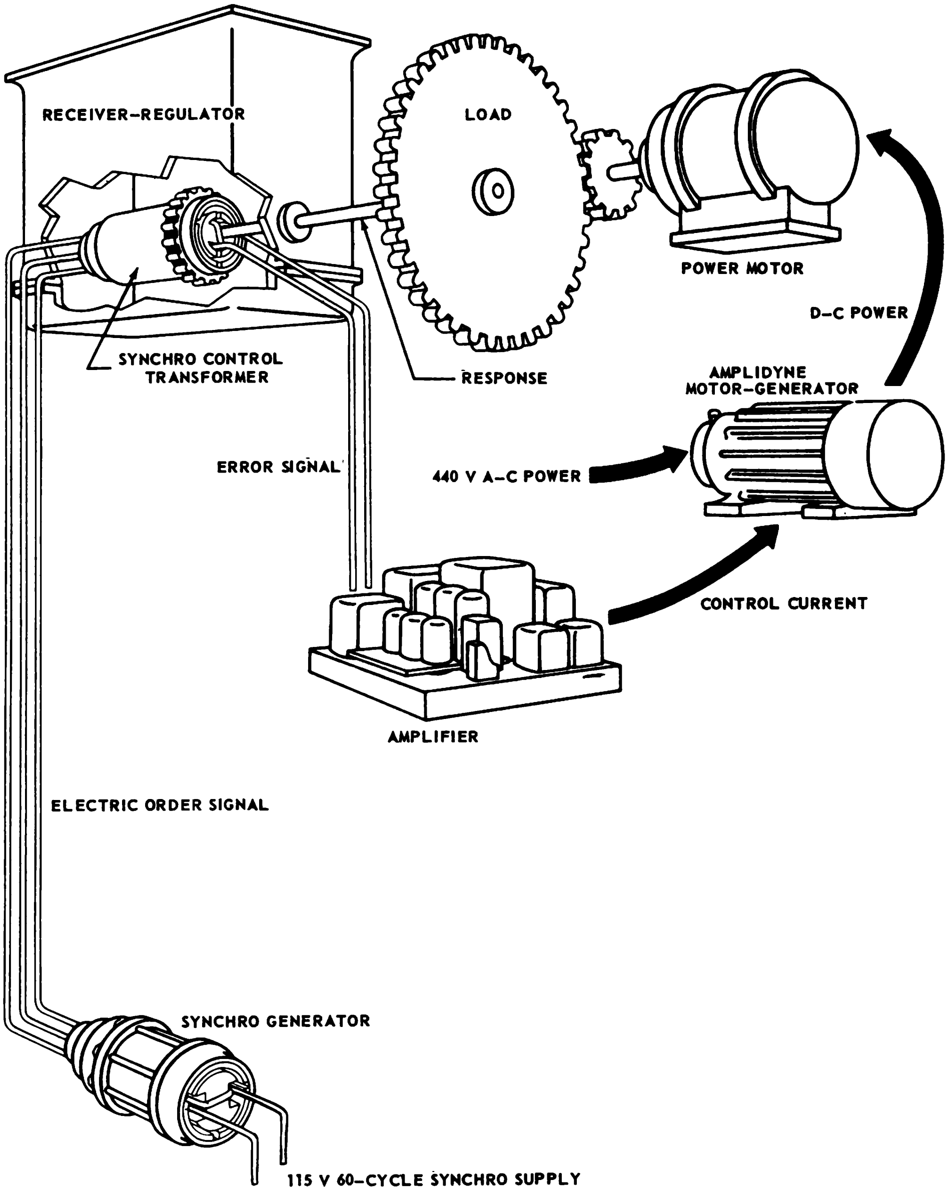


Figure 4-1.—Basic amplidyne drive.

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load. This current passes through the compensating winding, which creates a magnetic field. The compensating winding magnetic field and the load current magnetic field cancel each other.

This is fundamentally how an amplidyne generator works, although other refinements are necessary to achieve the fast, stable operation needed in a fire control system.

DRIVE MOTOR

The drive motor is a d-c motor of conventional design, having an armature circuit and a magnetic field. In the permanent-magnet type of d-c motor, the magnetic field is supplied by permanent magnets built into the stator. In the separately excited type the magnetic field is provided by a stator winding which receives

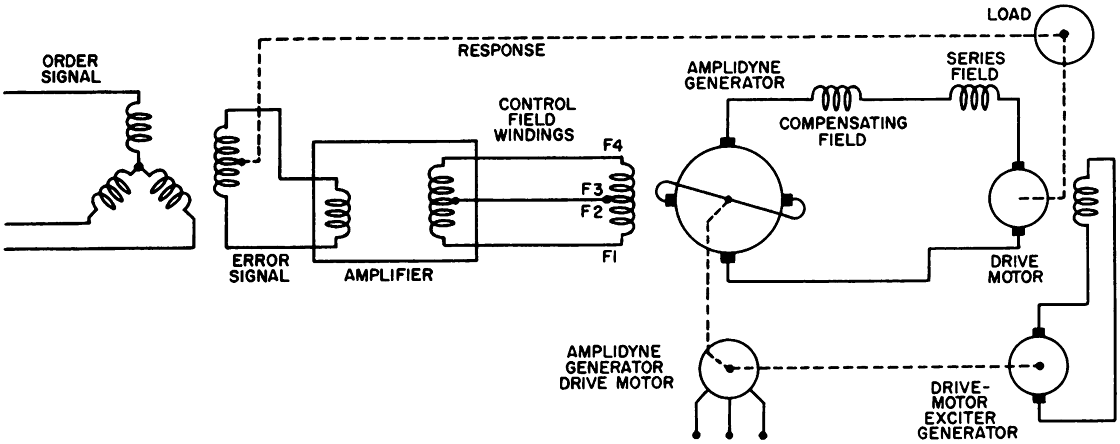

Figure 4-2.—Simplified diagram of the amplidyne generator and associated circuits. 55.46

a steady d-c current from a source separate from the motor. In both types, the armature current comes directly from the amplidyne generator.

The drive motor has a steady excitation field. Thus the direction of rotation depends only on the direction of the current in the armature. The turning force, or "torque," applied by the motor to the load depends on the volume of this current. Therefore, the motor's direction of rotation and torque depend on the output of the amplidyne generator.

GUN DIRECTOR MARK 37 AMPLIDYNE DRIVES

The preceding section of the chapter considered only the fundamentals of a basic amplidyne drive. In the rest of the chapter we will deal with the amplidyne drives used in the control of Gun Director Mk 37. We are primarily concerned, however, with the theory of the amplidyne drive rather than the operation of the director. Therefore, we will not consider those features of the drive which will not aid us to understand the drive's underlying principles. The MK 37 has three separate amplidyne drives—train, elevation, and crosslevel. Where the director requires a parallax correction, a fourth amplidyne drive is added. The parallax drive will not be discussed as such, for its circuits are similar to those in the other drives. Furthermore, where circuits in the train, elevation, and crosslevel drives are exactly alike, one explanation will be used for all three.

TRAIN DRIVE

Figure 4-3 shows the train circuit for the Mk 37. It contains the train synchro circuit, the 36-speed control transformer (CT) which furnishes the error signal to the amplifier through the input transformer T1. The CT also supplies the same error signal to the synchronizing circuit (T6, V6, and K1). The amplifier has two stages. The first stage (tubes (V1 and V2) is a converter demodulator. The second stage (tubes V3 and V4) is a push-pull power stage. The d-c voltages for this stage are supplied by the full-wave rectifier circuit (T2, V5, filter circuit T5 and C5, and the voltage divider circuit R10, R11, and R12). The output of the amplifier is fed to the control field of the amplidyne generator. The output of the generator is applied to the train motor. Stabilizing voltages are supplied to the amplifier by the stabilizing tach, the series field in the drive motor, and the generator quadrature field. These voltages are combined, and the combined voltage is an input to the amplifier via the various potentiometers, resistors, and condensers.

The amplifier circuits in all three drives are similar, so the explanation of the train amplifier will apply to the other amplifiers. The stabilizing and synchronizing circuits in the three drives are not alike, and will therefore be explained separately.

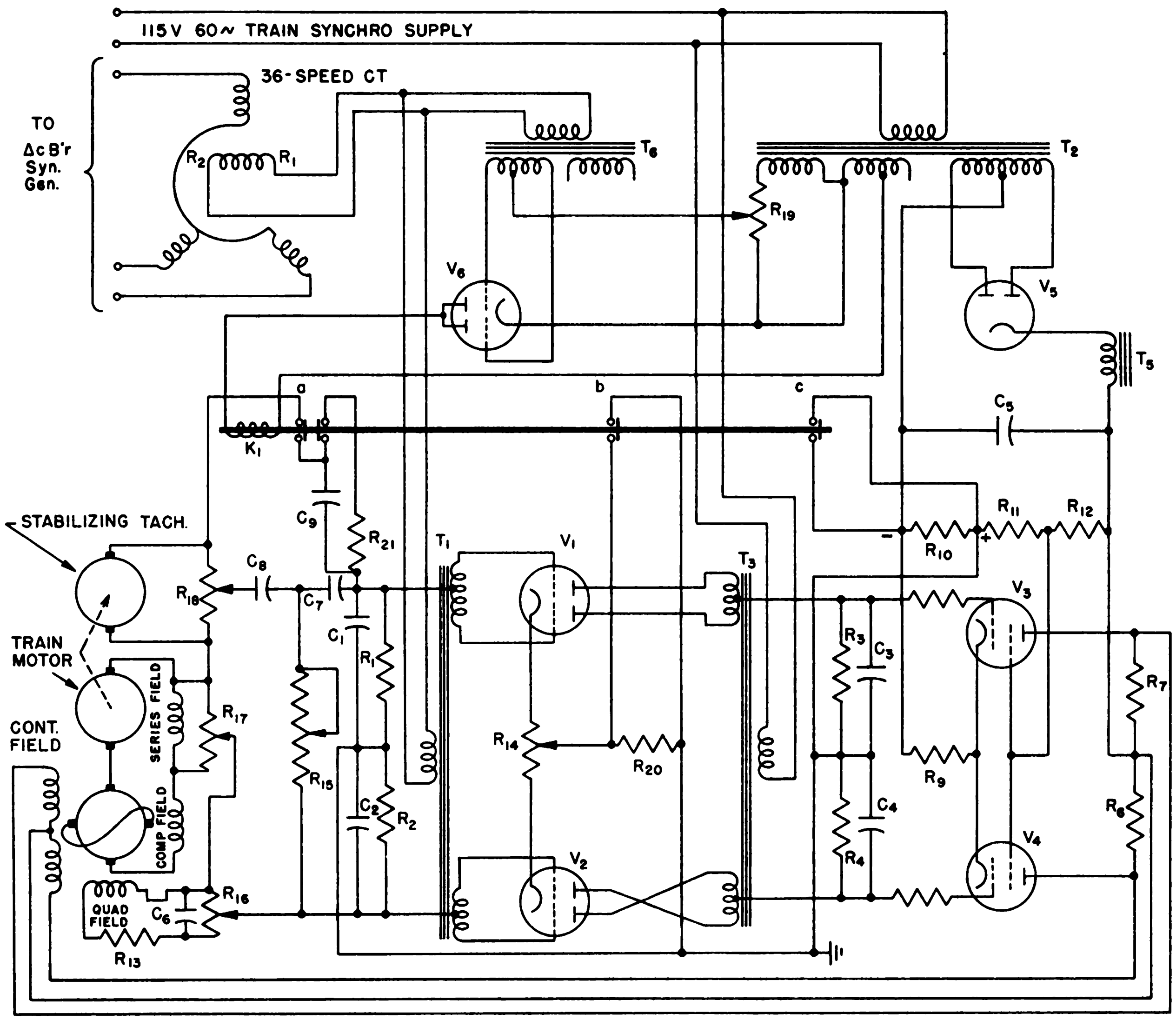

Figure 4-3.—Train circuit.

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Train Amplifier

The amplifier has two stages—the converter stage and the output stage. The converter stage produces two direct currents, one of which is greater when the error signal calls for the director to move in one direction, the other when the director should move in the opposite direction. When the error signal is zero the currents are equal. To provide these two currents, the converter stage rectifies and amplifies the error signal. The direct currents are used to control the output stage, which provides further amplification. The outputs of the amplifier control the amplidyne generator.

CONVERTER STAGE.—The converter stage is shown in figure 4-4. This stage compares both the phase and the magnitude of the a-c error signal from the control transformer with that of a reference voltage taken from the synchro supply. The error signal is either in phase or 180° out of phase with the reference voltage. The magnitude of the error signal

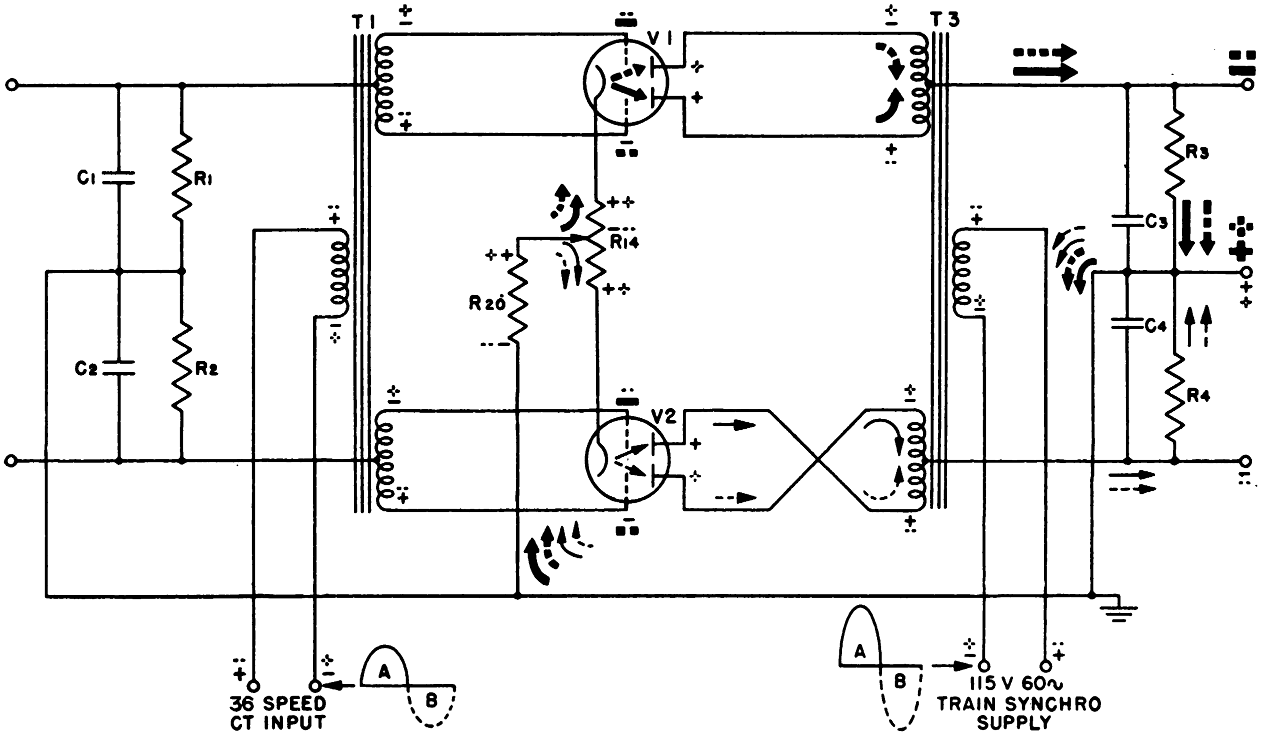

Figure 4-4.—Train converter circuit.

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will vary, whereas the value of the reference voltage is constant. The outputs of the converter stage are two d-c voltage potentials. This circuit is similar to the triode demodulator you studied in chapter 3 of this course.

The plates of V1 and V2 in figure 4-4 are connected to opposite ends of the secondary windings of transformer T3. The tubes' circuits will therefore act as full-wave rectifiers. Since the grids are connected to opposite ends of transformer T1, the circuit will compare the phase relationship between the a-c voltage inputs. The instantaneous polarities shown in the figure are for an in-phase right-train terror signal. With these polarities, tube V1 will conduct heavily. First one section and then the other section of the tube will have its plate and grid positive at the same time. The plate circuit for V1 is through a part of the winding of T3, down through R3, and back to the cathode through the common cathode resistor R20 and a part of potentiometer R14. Notice that the current through R3 is always in one direction.

Meanwhile back at V2 the plate that is positive will have a negative grid. The tube will conduct a slight amount under these conditions. Its plate circuit is through a part of T3, up through R4, and back to the cathode through R20 and a portion of potentiometer R14. The current through R4 will always be in one direction.

When the error signal is out of phase with the reference voltage, V2 will conduct heavily, and V1 slightly. The outputs of the converter circuit are the d-c potentials taken from the top of R3 and the bottom of R4. These potentials are applied to the grids of the second stage of the amplifier. With a zero error signal, the two potentials are equal. When an error signal is introduced into the converter, these potentials swing in opposite directions. Condensors C3 and C4 smooth out the voltages received from the first stage.

Resistors R1 and R2 and condensers C1 and C2 are part of the stabilizing voltage input circuit to the amplifier. This circuit will be covered later.

BALANCE ADJUSTMENT.—As explained earlier, the two control-field currents in the amplidyne generator should be equal when the error signal is zero. To provide equal outputs from the amplifier for a zero error signal, a circuit balance adjustment potentiometer R14 is connected in the cathode circuits of tubes V1 and V2, as shown in figure 4-4.

The potentiometer, R14, and the common cathode resistor, R20, provide self-bias for both V1 and V2. One end of the potentiometer controls the bias on tube V1, and the other end the bias on tube V2. By moving the potentiometer finger, the bias on one tube will be increased and the bias on the other decreased. Thus the output of the amplifier to one control field is increased and that to the other is decreased. The adjustment has been properly made when equal control currents are obtained with a zero error signal.

OUTPUT STAGE.—The output stage consists of tubes V3 and V4 and their related circuits, as shown in figure 4-5. The tubes receive a negative bias voltage from the d-c outputs of the converter stage. When these potentials are equal, the outputs of the tubes are equal. The grid of V3 receives a potential from the top of R3. This is a negative potential produced by the current flow down across R3. Thus an increase in this current will increase the negative potential applied to the grid of V3. This naturally will reduce the current flow through V3. A decrease in current flow across R3 will have an opposite effect on the current flow through V3.

The grid of V4 receives its bias from the bottom end of R4. The negative potential at the bottom of R4 has the same effect on V4 as that of R3 and V3.

An error signal present in the converter stage will result in the two d-c potentials swinging in opposite directions. This means that tubes V3 and V4 will receive opposite-going signals. Thus, one tube will have an increase in conduction while the other tube will have a decrease in conduction. The plates of the tubes are connected to the control windings in the amplidyne generator. The control fields will no longer cancel, and the amplidyne will have an output.

Tube V5 is a full-wave rectifier of conventional design which furnishes plate supply for the output stage. Resistors R10, R11, and R12 form a voltage divider network. Notice that R10 is between the cathodes and control grids of the tubes, and furnishes positive bias voltage to the tubes.

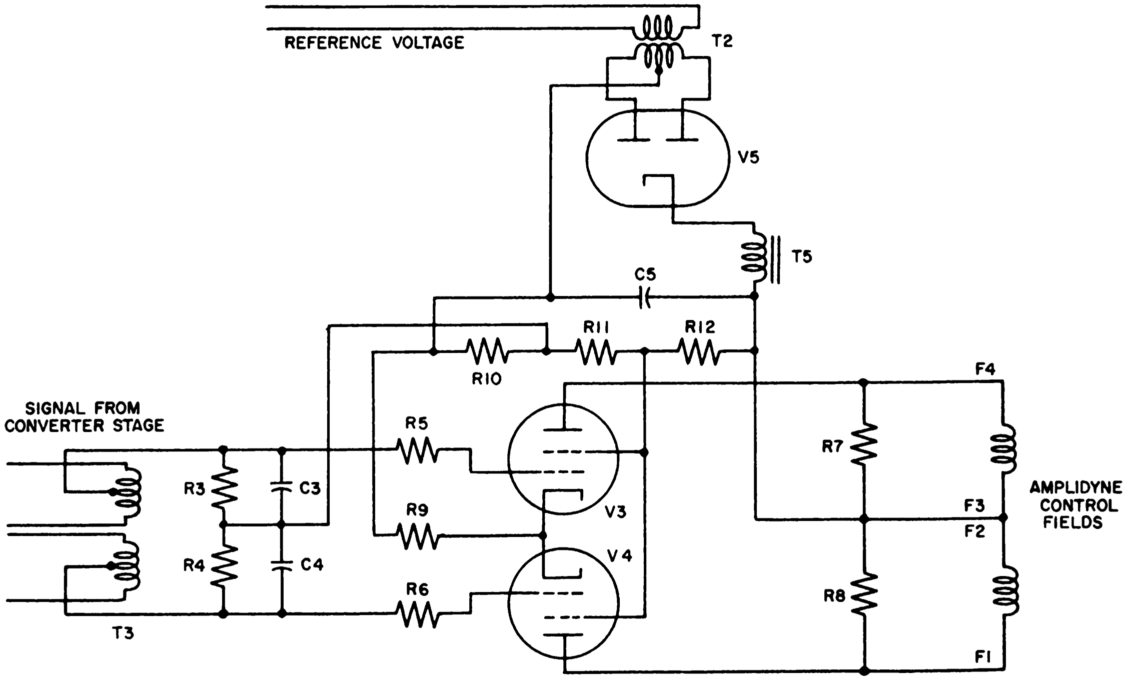

Figure 4-5.—Output stage of the amplifier.

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Train Stabilizing Circuit

Before going into the train stabilization circuits, we will look at the characteristics of a followup system to determine why stabilization is necessary. In chapter 3 of this course we discussed stabilization, but did not tie it to a specific servosystem. Here the information is directed specifically to the amplidyne followup systems in Director Mk 37.

Here we will describe and define two types of oscillations found in a followup system. The first type of oscillation is called HUNTING. When the system is hunting, the control is unstable and oscillates about the point of correspondence. The oscillations are rather large. We will arbitrarily place the amplitude of the oscillation at greater than 10 minutes of arc.

The second type of oscillation we will call JITTER. In this condition the control is unstable and oscillates at a high frequency and with a low amplitude about the point of correspondence. This condition produces vibration, chatter, or rumble in the gear train.

Both hunting and jitter are reduced or eliminated by the stabilizing voltages. These voltages modify the effect of the error signal, but do not interfere with normal operation. There are three stabilizing voltages commonly used in amplidyne followup systems, namely, the speed, current, and jitter voltages. Figure 4-6 shows the source of these voltages in the Mk 37 train followup system.

SOURCE OF THE STABILIZING VOLTAGES.—The speed voltage is obtained from a d-c tachometer generator, which is geared to the train drive. This makes the generator output proportional to the director's speed. The output polarity depends upon the direction of movement of the director. In the diagram, you can see that this voltage is dropped across potentiometer R18.

The current stabilizing voltage is obtained from the series field of the drive motor. The voltage across the series field is proportional to the current drawn by the drive motor. This voltage is most effective when the drive motor draws heavy current, for example, at starts and reversals. This voltage is dropped across potentiometer R17.

To obtain a third stabilizing voltage, a special winding is built into the stator of the amplidyne generator (fig. 4-6). This winding

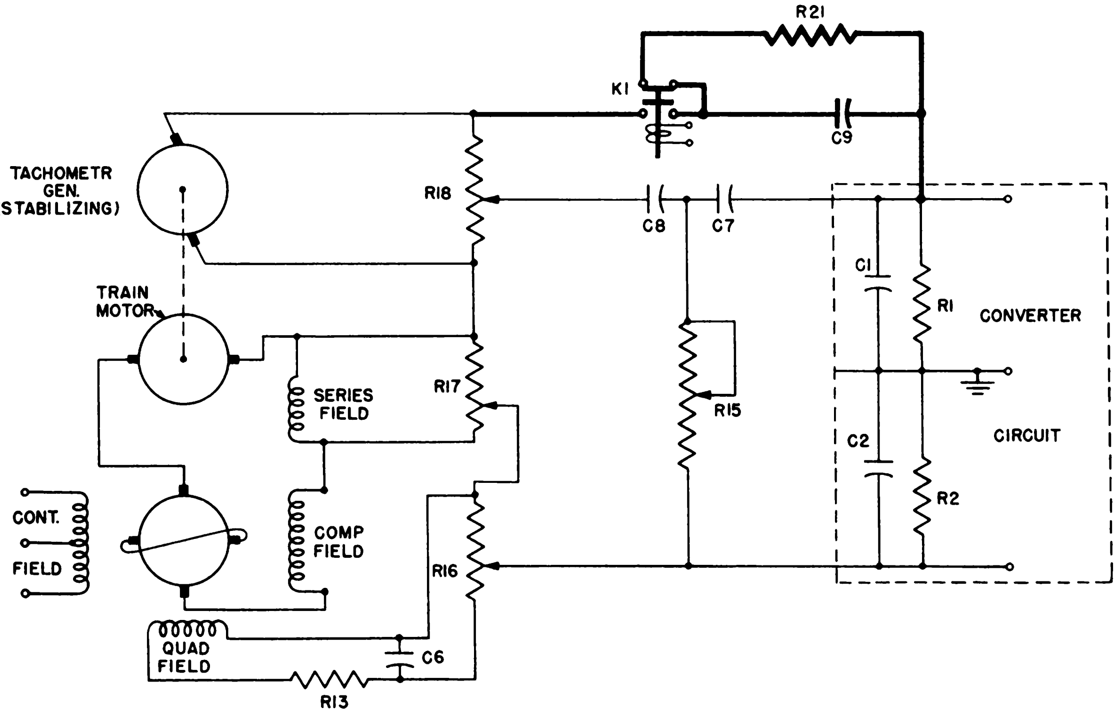

Figure 4-6.—Train stabilizing circuit.

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is called the quadrature winding; it is placed at a right angle to the control winding. In this position the quadrature winding is cut by the quadrature field. Since this field is created by a d-c current, it has a constant magnitude when a constant signal is applied to the generator. The flux lines of the quadrature field thread through the winding and do not induce a voltage. But when the strength of the quadrature field changes, a voltage is induced in the winding. This happens only when the load on the amplidyne changes. Thus, the voltage induced in the quadrature winding is proportional to the RATE of load change, and the frequency of this voltage is equal to the frequency of the quadrature flux changes.

The rate of load change is greatest when the director is reversing fastest during jitter. For this reason, the voltage in the quadrature winding is called the jitter stabilizing voltage. The jitter voltage is dropped across potentiometer R16.

Every followup system has one or more natural oscillating frequencies which depend on the weight of the load, designed speed of the system, and other characteristics. In the train amplidyne system al three of the stabilizing voltages are needed to control hunting and jitter. In other systems, the characteristics are such that only one or two of the signals are necessary.

COMBINING THE STABILIZING VOLTAGE.—As explained, each stabilizing voltage is used to overcome a particular type of oscillation. Since each of these voltages is applied to an adjustable potentiometer, the percentage of each voltage in the remainder of the circuit can be controlled. Therefore we can adjust the amount of each of these voltages to obtain the best operation of the director. The potentiometers are connected in series. Thus their output voltage will be the algebraic sum of the three voltage percentages.

The stabilizing voltages are direct current. As long as the director is operating normally, and is moving at a constant speed, condensers C7 and C8 will effectively block the d-c voltages (fig. 4-6). But when the director is oscillating, the polarity of the voltages is reversed on every swing, and they become low frequency a-c voltages. The resulting alternating current can pass through the condensers. The condensers and their associated resistors will pass the frequencies found in oscillations, but will block the lower frequencies in the range of the roll and pitch of the ship. Hence, they constitute a "high-pass filter." The result is that there is no appreciable current flow in resistors R1 and R2, except when the system is unstable.

The potentials developed across R1 and R2 are determined by the direction of director movement. The two potentials of opposite polarity are used to modify the error signal in the converter stage of the amplifier. The potentials are always in opposition to the error signal, and are thus a form of negative feedback.

Potentiometer R15 in figure 4-6 is in parallel with resistors R1 and R2. R15 provides a path for bypassing a part of the stabilizing current to adjust its total effect on the amplifier.

Train Synchronizing Circuit

The purpose of the synchronizing circuit is to prevent overspeeding of the drive when large error signals are present. This is done by reducing the sensitivity of the amplifier. The director is originally positioned by the target designation system or by the director trainer. When the director goes into automatic, the 36-speed error signal keeps the director on target. Since the signal is received from a 36-speed transmitter, synchronism can be obtained at 36 positions, each 10° apart. Thirty-five will be false positions and only one will be the true synchronizing point. If a large error signal is allowed to drive the equipment at an excessive speed and we have a radical change of target speed or direction, the inertia of the moving heavy equipment could become so great as to drive past synchronism in excess of 5 degrees, causing it to synchronize at a false point.

The principle parts of the synchronizing system are tube V6 and relay K1, shown in figure 4-3. V6 rectifies and amplifies the error signal from the control transformer. The output of V6 is used to energize relay K1.

Relay K1 will be energized and picked up for all error signals in excess of approximately 50 minutes of arc. When the relay is energized, it performs the following functions.

1. The contacts at point "c" short out resistor R10. This resistor normally supplies positive bias to the grids of tubes V3 and V4. Thus the gain of this stage is reduced.
2. The contacts at point "b" short out resistor R20, which supplies negative bias to tubes V1 and V2. This action increases the

output of these tubes. Since V1 and V2 furnish negative bias to V3 and V4, the amplifier output is further reduced.

3. The contacts at point "a" connect the whole stabilizing voltage of potentiometer R18 through capacitor C9 to the amplifier. The increased stabilizing voltage dampens the increased tendency toward instability which comes with high speed.

Since we want maximum sensitivity to small errors, relay K1 does not operate below approximately 50 minutes of error. The exact value depends upon the setting of potentiometer R19.

This means that the single 36-speed system will produce correct synchronism if overspeed is prevented. That's why the synchronizing circuit is designed to apply relay K1.

There is no need for this circuit when the error signal is less than 50 minutes. Therefore, the K1 relay does not operate below this amount of error. Also, eliminating the relay's circuits during small errors will increase sensitivity. This increases the accuracy for small errors.

The complete synchronizing relay circuit is shown in figure 4-7. The figure will be explained for a zero error, or for an error signal of less than 50 minutes. Let us trace out the plate and grid circuits for alteration B of the supply by following the broken arrows.

K1 is connected in series with the plate of V6 and whatever current flows through V6 also flows through K1. The plates of V6 are positive in respect to the cathode, and the grids of V6 are biased near cut off by the large voltage across the bottom secondary of T2. V6 passes only a small current through K1, insufficient to energize it.

The circuit in figure 4-8 shows what happens for a large left-train error signal. The error signal is added to the grids at T6, and this large error signal drives the bottom grid less negative. This action may be seen by checking the polarities in figure 4-8.

The less negative grid allows the plate current to increase to a value large enough to operate K1. When the contacts of K1 close, the amplifier gain is reduced and the director is slowed down.

Figure 4-9 shows a large right-train error signal. Trace out the circuit by following the broken arrows for alternation B. The top plate

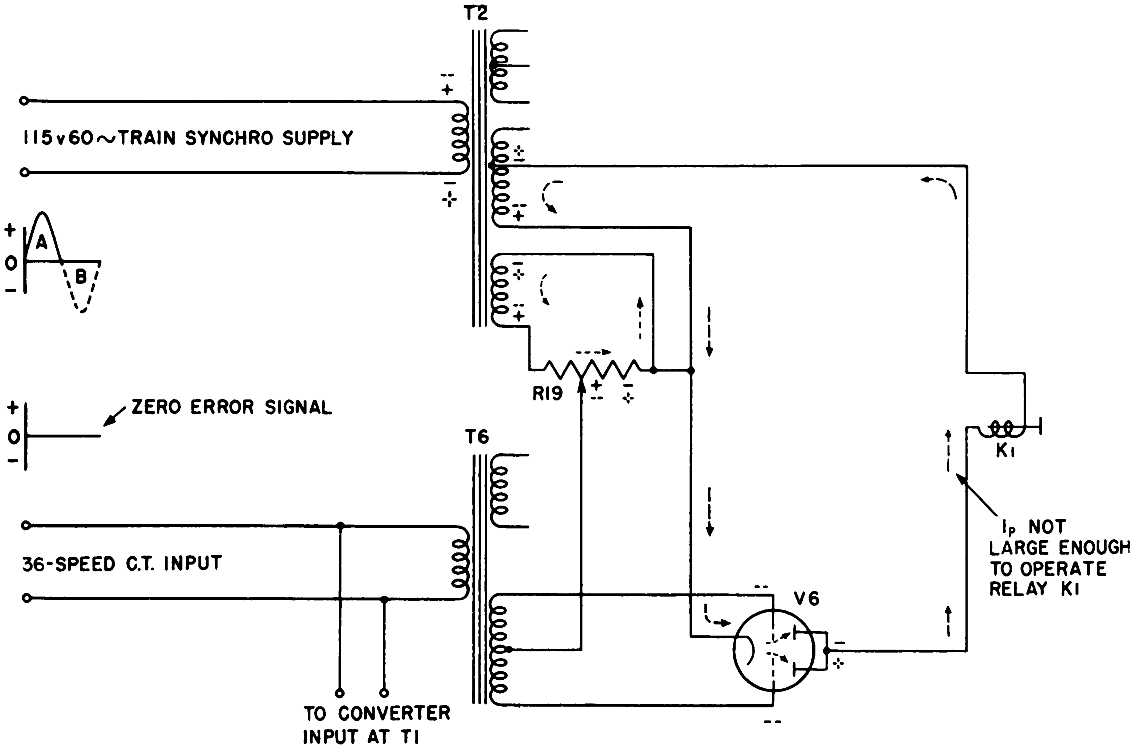

Figure 4-7.—Synchronizing circuit, no signal.

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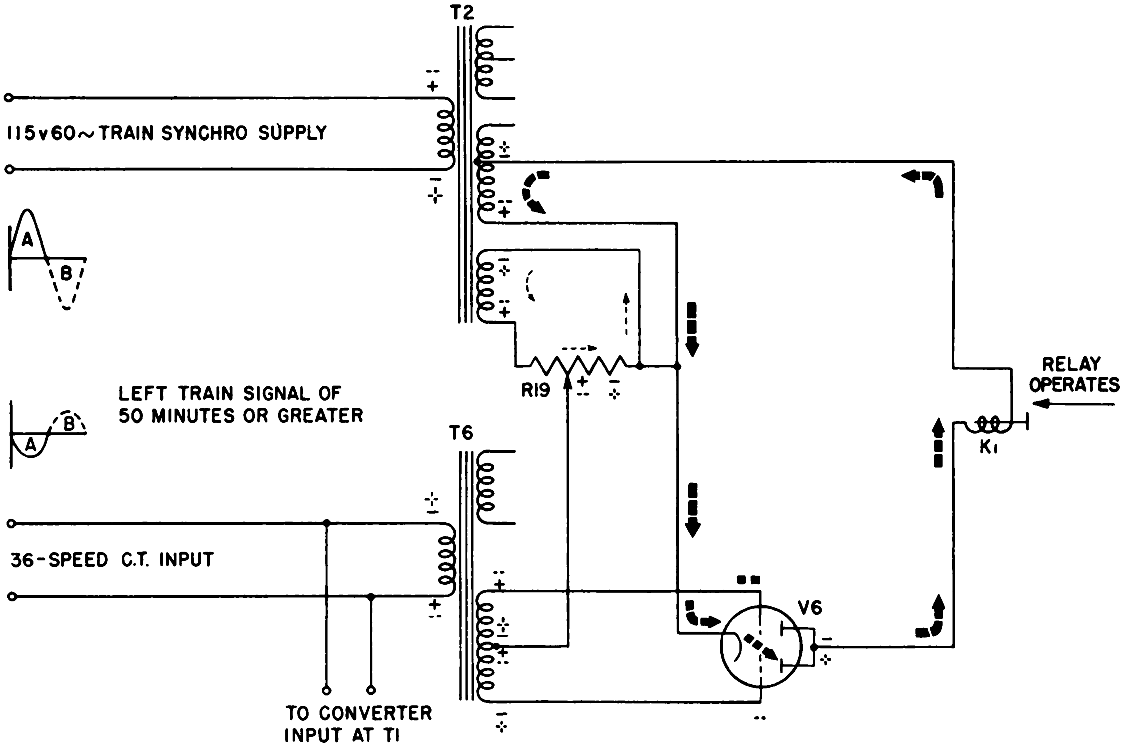

Figure 4-8.—Synchronizing circuit, left train.

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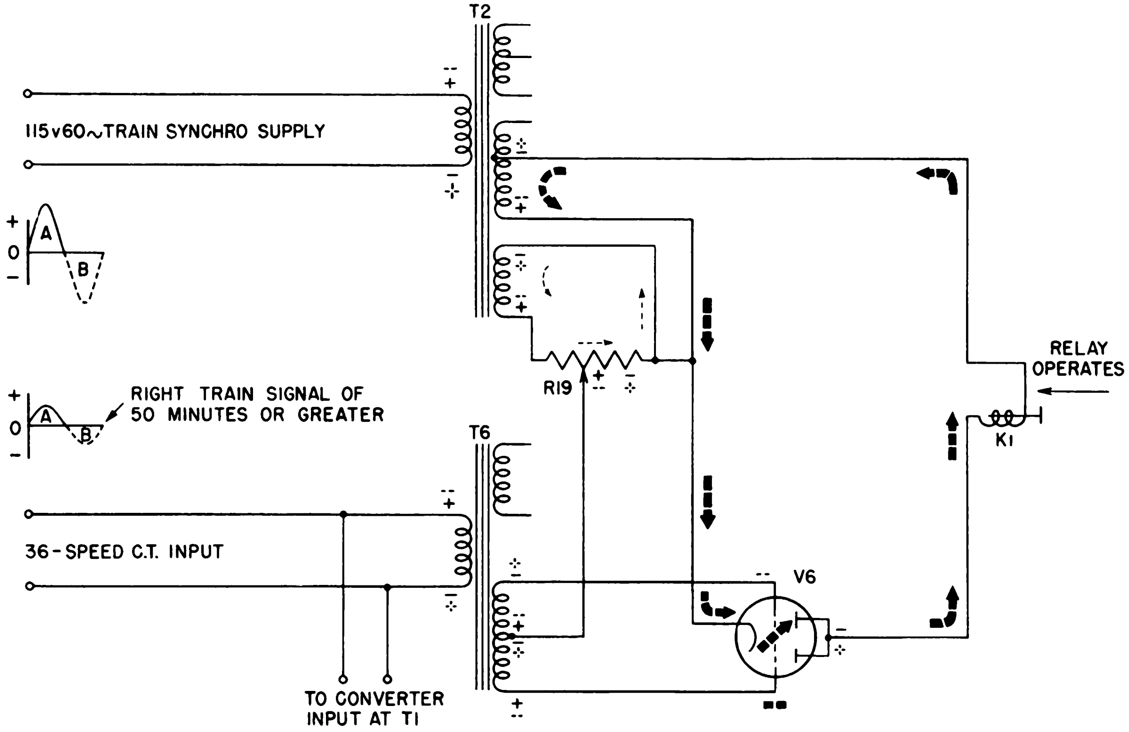

Figure 4-9.—Synchronizing circuit, right train.

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of V6 now has the large plate current which closes the contacts of K1.

You're probably wondering what happens during alternation A. During alternation A the plates of V6 are negative. Since the plates are negative no current will flow, thence, no current through K1. K1 relay is designed to operate on half-wave pulses, which means that 60 pulses a second will hold K1 closed. Therefore, it does not fall out between the B alternation pulses even though no current flows through K1 during the A alternation.

CROSSLEVEL CONTROL CIRCUIT

The converter and the amplifier circuits in the crosslevel control are just like the converter and amplifier circuits in the train control. The stabilizing and synchronizing circuits are different, however, and will be explained.

Crosslevel Stabilizing Circuit

The crosslevel stabilizing circuit does the same job as any other stabilizing circuit—it removes hunt and jitter. It does its job in about the same way as the train circuit by feeding voltages into the converter circuit to oppose the signal.

The new and different parts of the crosslevel stabilizer are the sources of the stabilizing voltages, as shown in figure 4-10.

The current feedback voltage in figure 4-10 is tapped across the series field of the drive motor. This voltage goes into the stabilizing circuit at R17.

The speed feedback voltage at the finger of R18 is tapped across the amplidyne output terminals. This voltage is proportional to the speed of the drive motor, because the amplidyne output voltage depends on the amplidyne load. The amplidyne load is the drive motor. As the motor speeds up, counter emf reduces the load so the amplidyne terminal voltage increases. This speed feedback voltage goes into the stabilizing circuit at R18.

The jitter feedback voltage comes from the quadrature winding and this voltage goes into the stabilizing circuit at R16.

The current and speed feedbacks are combined across R19, R20, and R21. R19 adjusts

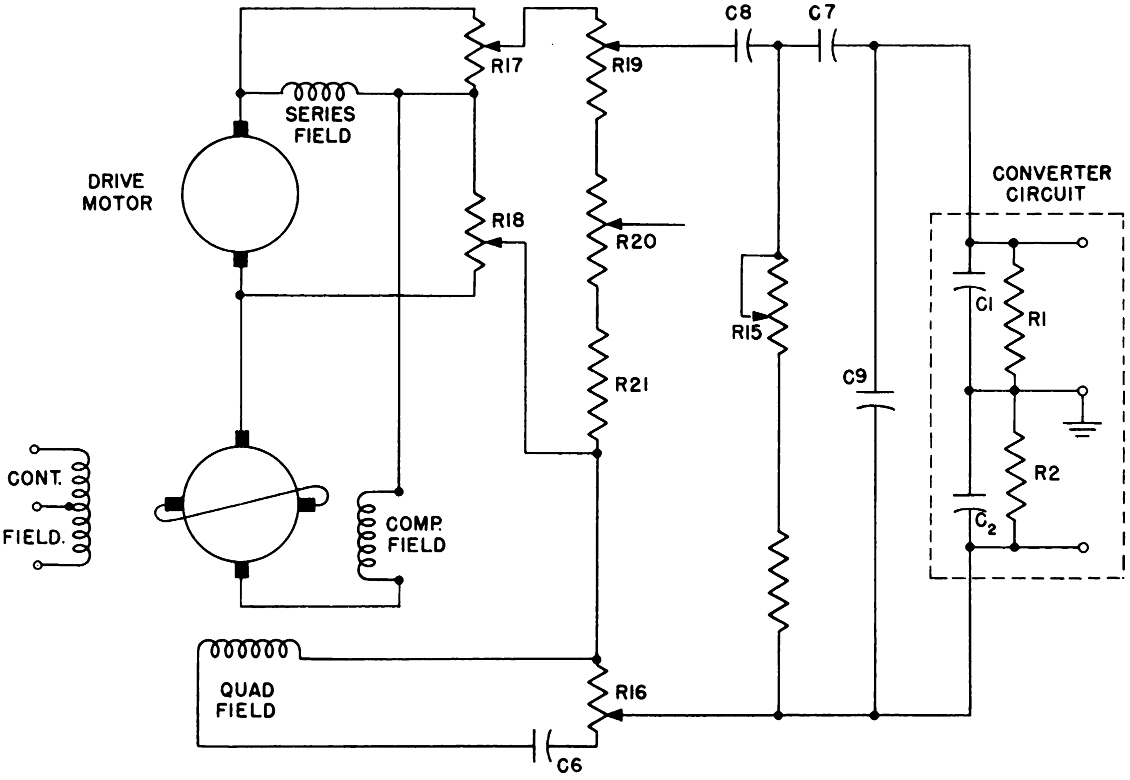

Figure 4-10.—Crosslevel stabilizing circuit.

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the amount of this combined feedback and then the combined current and speed feedback is added to the jitter feedback at R16.

A high-pass filter C7, C8, R15 removes low frequency feedback. Thus, only the hunt and jitter feedbacks get into the converter circuit.

Finally, the total stabilizing feedback is fed to the converter circuit across R1 and R2.

Condensors C1, C2, and C9 provide a bypass circuit for stray high frequency voltages.

Crosslevel Synchronizing Circuit

The crosslevel synchronizing and stabilizing circuits are shown in figure 4-11.

For errors of 80 minutes or more, the synchronizing circuit feeds the 2-speed CT signal to the converter. For errors of less than 50 minutes, it cuts out the 2-speed CT signal and feeds in the 72-speed CT signal.

Here's what the synchronizing circuit does. V6 is biased near cutoff, but when the error exceeds 80 minutes, one of V6 grids allows enough current to pass through V6 to operate K3, which opens the contacts at point a. This interrupts the 72-speed CT signal at T1. At the same time, K3 closes the contacts at points b and c. This completes the synchronizing circuit as shown by the heavy lines in figure 4-11.

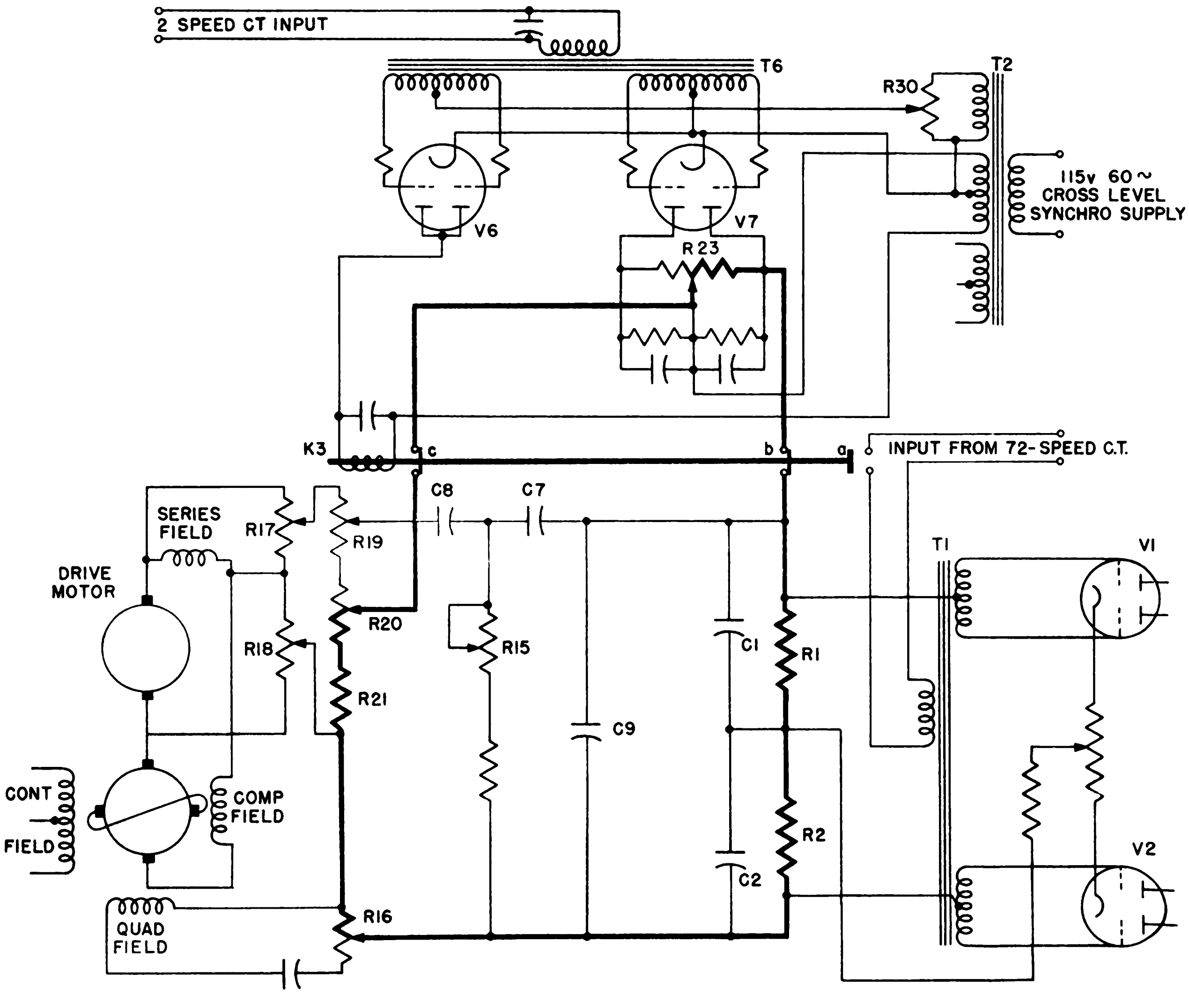

Figure 4-11.—Crosslevel synchronizing circuit.

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The synchronizing voltage is the amplified and rectified 2-speed CT signal It comes from V7 and is fed into the synchronizing circuit across R23. This R23 voltage is ADDED to the stabilizing feedbacks at R20, R21, and R16. Finally, the combined synchronizing and stabilizing voltages are fed to the converter at R1 and R2.

Notice that K3 also bypasses C7 and C8. Thus, during coarse control, the d-c current and speed feedbacks are added directly to R1 and R2. These d-c feedbacks brake the amount to prevent any overspeeding that might result from overlarge error signals.

SYNCHRONIZING CIRCUIT DETAILS.—You know what the synchronizing circuit does. Now find out how it works. Look at figure 4-12.

The PHASE of the error signal from the 2-speed CT depends on whether the crosslevel angle is increasing or decreasing. In this case the error signal is out of phase for an increasing angle.

Figure 4-12 shows the synchronizing circuit in detail. The diagram is polarized for an OUT-OF-PHASE error signal of more than 80 minutes.

First, trace out the plate supply for V6 and V7. Both tubes get their plate supply from the middle secondary of T2. T2 is energized by the crosslevel synchro supply. The error signal is out of phase with this supply voltage.

Now check the plate polarities in figure 4-12. Both V6 plates are positive for alternation B, and both V7 plates are positive for alternation A. This means that V6 can pass current only during alternation B, and V7 can pass current only during alternation A.

Follow the operation of V6 which is biased nearly at cutoff by the top secondary of T2. But the error signal at T6 REDUCES this bias. When the error signal exceeds 80 minutes, the bias is reduced enough so that the V6 current operates K3. Although V6 passes current only on alternation B, this pulsating current holds the K3 contacts closed. By following the broken arrows in figure 4-12, you can trace out the operation of V6.

Now use figure 4-12 to trace out the operation of V7 for NO-SIGNAL at T6. The two plate currents of V7 are equal. This balances the voltages across R28 and R29—there is no current through R23 and no output to the converter.

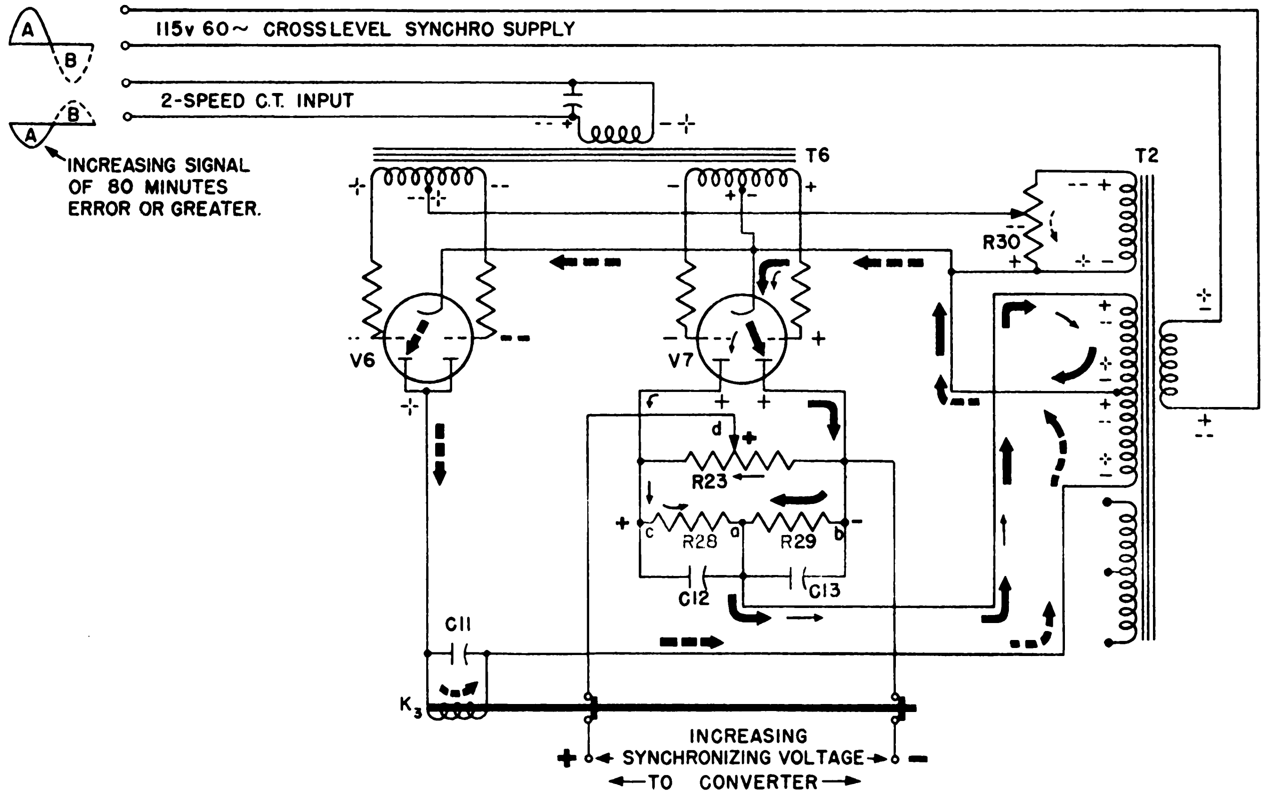
A
B
115v 60~ CROSSLEVEL SYNCHRO SUPPLY
2-SPEED C.T. INPUT
B
A
INCREASING SIGNAL OF 80 MINUTES ERROR OR GREATER.
T6
T2
R30
V6
V7
d
R23
c
R28
a
R29
b
C12
C13
C11
K3
INCREASING SYNCHRONIZING VOLTAGE
TO CONVERTER

Figure 4-12.—Synchronizing circuit, out-of-phase signal.

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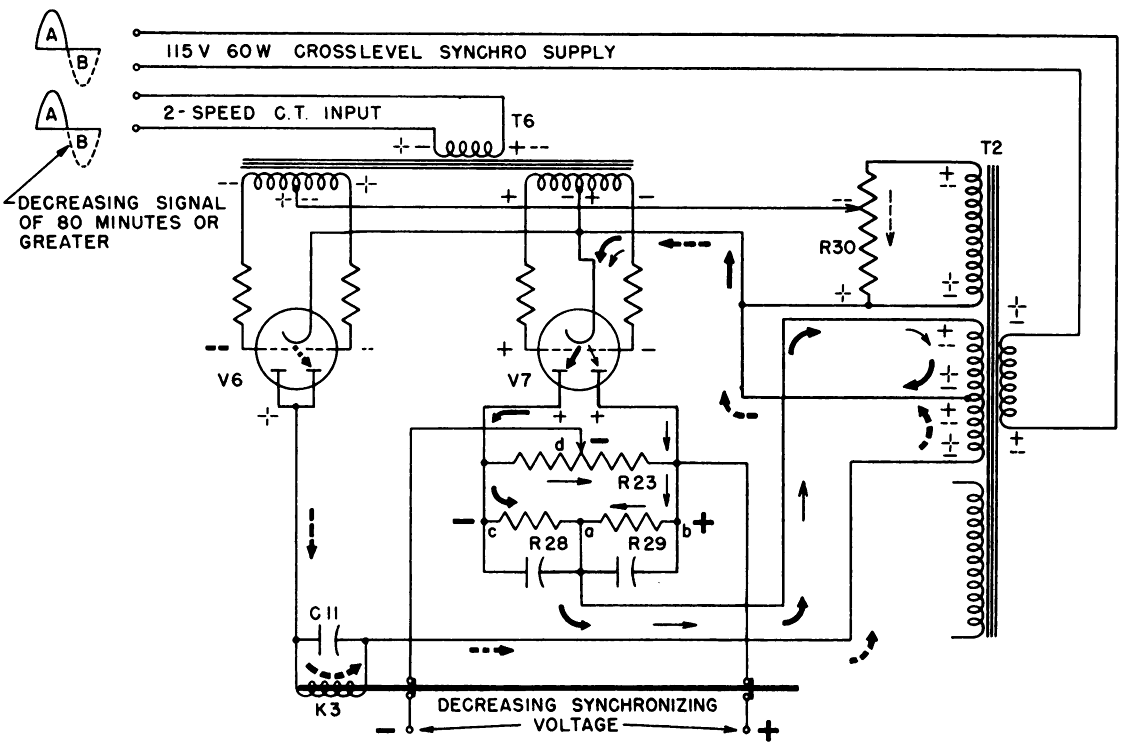
115V 60W CROSSLEVEL SYNCHRO SUPPLY
2-SPEED C.T. INPUT
T6
T2
A
B
DECREASING SIGNAL OF 80 MINUTES OR GREATER
R30
V6
V7
d
R23
c
R28
a
R29
b
C11
K3
DECREASING SYNCHRONIZING VOLTAGE

Figure 4-13.—Synchronizing circuit, in-phase signal. 55.57

Now trace out the V7 operation for an OUT-OF-PHASE signal at T6. The signal drives the left-hand grid more negative, and the right-hand grid less negative. The R29 current increases and the R28 current decreases. This makes point b negative with respect to point c.

The b-to-c voltage is across R23, and it forces a current through R23. Point d in R23 becomes positive with respect to point b. Finally, this b-to-d potential becomes the converter input. C12 and C13 filter the pulses from V7. Thus, the R23 voltage to the converter is fairly steady.

You'll understand the operation of V7 by following the solid arrows in figure 4-12.

Figure 4-13 shows the synchronizing circuit operating with an IN-PHASE signal of 80 or more minutes of error. For the in-phase signal, the opposite plate of V6 conducts. The result is the same—K3 operates to close its contacts.

Trace out the V7 plate and grid circuits in figure 4-13. Notice the V7 grid polarities; they are opposite to the polarities for an out-of-phase signal. Result—the R23 current is reversed. Now point d is negative with respect to point b, and this d-to-b potential becomes the input to the converter circuit.

You can trace out the V7 operation by following the solid arrows in figure 4-13.

Before you leave the synchronizing circuit for the crosslevel amplidyne control, go back to figure 4-11 and trace both in-phase and out-of-phase signals through this complete circuit. Be sure to see how signals of more than 80 minutes of error operate the synchronizing circuit. V6 controls K3 to open the fine CT circuit and close the coarse CT circuit. V7 rectifies and amplifies the coarse CT signal. Finally, the coarse CT signal is combined with the stabilizing voltages and fed to the converter circuit.

ELEVATION CONTROL CIRCUITS

The elevation stabilizing circuit is just like the cross level stabilizing circuit, and the elevation converter-amplifier circuit is just like the train and cross level converter amplifiers.

The elevation circuit has NO SYNCHRONIZING circuit. It does not need a synchronizing circuit because the elevation gear is LIGHT. There is no danger of the elevation gear overspeeding and overdriving into the next point of synchronism.

CHAPTER 5

FIRE CONTROL RADAR

The basic concepts of pulse radar are explained in the Navy Training Course, Basic Electronics, NavPers 10087-A. This chapter extends these concepts, and introduces some fairly recent radar techniques. As you study this chapter, keep in mind that the subject matter is so broad that complete coverage is not attempted. Instead, only general background information that will help you understand the operating principles of specific radar equipment is included.

Until recently the word radar in a text referred to pulsed radar. This is no longer true. There are many other techniques in use for transmitting electromagnetic energy. Besides pulsed radar, you must now become familiar with continuous-wave radars and radars that use combinations of pulse and c-w techniques. In order to understand these concepts, the basic principles of c-w radar and the Doppler effect must be understood first. It is assumed that you have a basic background in pulse radar; therefore, the coverage of pulse techniques in this chapter is limited to a brief review of basic sections.

PURPOSE OF RADAR

Radar increases the effectiveness of naval fire power by adding new capabilities to the human senses. It is unhampered by obstacles such as darkness, haze, fog, and smoke. Radar reveals the presence of objects far beyond the normal range of vision. A radar set not only detects targets but indicates their range, bearing, and elevation with a high degree of accuracy.

In some respects, radar detection is inferior to normal vision. Radar presentations reveal little target detail. There is not much you can tell about a target except its location. The ability of radar to distinguish between various objects is limited. Sometimes it presents unwanted echoes from sea waves and land (called clutter) as readily as targets of interest. Also, radar is subject to willful interference or jamming by the enemy.

CLASSES OF RADARS

Fire control radars may be classified by their general use, by their method of modulation, by their frequency or wavelength, by their method of scanning, or more frequently, by their method of transmission. Of course, there are other methods of classification, but the ones listed are used most frequently.

When fire control radars are classified according to use or the weapon they direct, they can be divided into two general categories (1) gun fire control radars, and (2) missile fire control radars. It would be possible, and correct, to include another category called gun and missile fire control radars, because some fire control radars determine the position of enemy targets and direct the ship's guns and missile launchers simultaneously. But for our purposes let's stick to the two categories listed above.

Basic Principle Of Radar

Regardless of classification, radar works on the echo principle. A radar set radiates waves of r-f energy. When these waves strike an object, some of the r-f energy is reflected back as an echo. The characteristics of the reflected wave depend partly on the characteristics of the primary wave. The amount of energy reflected depends on the size and nature of the reflecting surface.

When the echo returns to the radar set, the radar detects or "sees" a target. For the radar set to be really useful, it must supply continuous target location and range information. First let's look at some of the target detection techniques used by the Navy. Then we will cover the various methods of radar ranging, and of pinpointing targets.

TARGET DETECTION METHODS

This section discusses the types of transmission, the effect of the target on the transmitted energy, and the interpretation of the reflected energy which results in target detection. The two basic methods of transmission are the continuous-wave method and the pulse method.

CONTINUOUS-WAVE METHOD

The continuous-wave (c-w) radar continuously radiates r-f energy of a constant frequency. These waves of energy strike the target and are reflected. If the target is moving toward or away from the radar, the reflected signal is shifted in frequency. This shift in the frequency of the reflected energy is due to a characteristic of wave motion called Doppler effect or Doppler shift. The difference between the transmitted frequency and the echo frequency is used for target detection.

The Doppler Effect

This principle, which bears the name of its discoverer, Christian Doppler, pertains to the shift, or change in frequency of a series of waves, that occurs when there is relative motion along the line of transmission of energy between the source and the receiver of these waves. Some examples of waves that can be frequency shifted are sound, light, infrared, radio, and radar. A simple illustration of the Doppler effect in terms of sound waves is familiar to anyone who has observed the change in pitch of a train whistle as it approaches or recedes rapidly. When approaching, the sound-producing whistle comes a little nearer between each two successive waves it emits; and the waves strike the ear in more rapid succession, so that the frequency becomes greater and the pitch rises.

If the train is moving away from the observer, the interval between successive waves is slightly increased, the frequency received by the ear is somewhat decreased, and the pitch is lowered as a result. If the frequency of the sound received when the train is at rest is measured and compared with the frequency received when the train is in motion, there is a difference in the two values called the DOPPLER SHIFT. This frequency difference could then be used to measure the speed of the train with respect to the observer.

A continuous-wave radar operates by means of the same effect, except that electromagnetic waves are employed instead of sound. The transmitting antenna of the radar set beams uninterruped energy of a constant frequency toward the target. The target reflects the energy, and becomes in effect a second emitter of waves. If target motion is in the line of sight with respect to the radar, the frequency of the returning echoes differs from that of the outgoing signals. The echoes are picked up by the antenna and are heterodyned in the receiver with a small reference voltage at the frequency of the outgoing waves. The difference value, or beat frequency, which results from mixing the reference and echo voltages, is the Doppler signal. The presence of this signal indicates a moving target. And as in the example of the moving train whistle, the Doppler value in cycles per second serves as a measure of the relative speed (range rate).

In textbooks that deal with the Doppler effect, it is shown that in two-way travel of electromagnetic waves, as in the c-w radar system, the amount of frequency change in cycles (f_d) is related to the relative speed in the line of sight (V_c) by a simple equation,

$$f_d = \frac{2V_c f}{c} \qquad \text{(eq. 5-1)}$$

in which f is the frequency of the reference signal, and c is the velocity of the radar waves. If the relative velocity is measured in miles per hour, since $\frac{c}{f}$ is the wavelength (λ) of the reference emission, the equation can be expressed in the following form:

$$f_d = \frac{89.4V_c}{\lambda} \qquad \text{(eq. 5-2)}$$

where f_d is in cycles per second, V_c is in miles per hour, and the wavelength, λ, is measured in centimeters. (The constant required to convert miles per hour to centimeters per second is 44.7; 2 x 44.7 = 89.4.)

If the c-w radar emits radiation with a wavelength of 10 centimeters, then according to equation 5-2, the Doppler signal will vary by almost

9 cycles per second for each mile per hour of range rate. If the radiation has a wavelength of 3 centimeters, a typical value in microwave systems, then the Doppler shift amounts to almost 30 cycles per second for each mile per hour of range rate. For example, assume that the range rate for a certain air target is 600 miles per hour and the c-w radar system employs 3-centimeter radiation. When these figures are substituted in equation 5-2, the resulting Doppler frequency is 17,880 cps. This would mean that the returning echo from the target would be either 17,880 cps higher or lower than the transmitted frequency. Let's take a basic c-w radar and see how this information is obtained and used.

BASIC C-W RADAR SET

The basic c-w radar set consists of a transmitter, a receiver, an indicator, a transmitter antenna, and a receiver antenna. This arrangement is shown in figure 5-1. The transmitter generates a continuous wave of r-f energy. This energy is radiated by the transmitter's antenna. A low power sample of the r-f energy is sent to the receiver to be used as a comparison frequency. When the radiated energy strikes a target, a portion of the energy is reflected back to the radar and picked up by the receiver's antenna.

If the target is moving toward the transmitter, the frequency of the echo is higher than the transmitted frequency. If the target is moving away, the echo frequency will be less than the transmitted frequency. Finally if the target is not moving the echo frequency will be the same as the transmitted frequency. The transmitted frequency, in the echo, is for all practical purposes a carrier frequency which has been modulated by target's range rate. The returned echo is fed from the receiver antenna to the receiver.

The receiver contains a local oscillator whose output frequency L_o is beat in the first mixer with the sample of r-f energy f_o. The beat frequency $(f_o + L_o)$ is fed to a second mixer. In this mixer the echo return $(f_o \pm f_d)$, transmitted frequency ± Doppler shift, and $f_o + L_o$ are beat together. The output of the mixer is $L_o \pm f_d$. This frequency is amplified and fed to a discriminator. The discriminator is a frequency error-detecting circuit which is resonant at the L_o frequency. The purpose of the discriminator is to develop a d-c voltage output with a polarity that is determined by the direction of frequency shift from the L_o frequency and that has an amplitude that is determined by the amount of frequency variation from

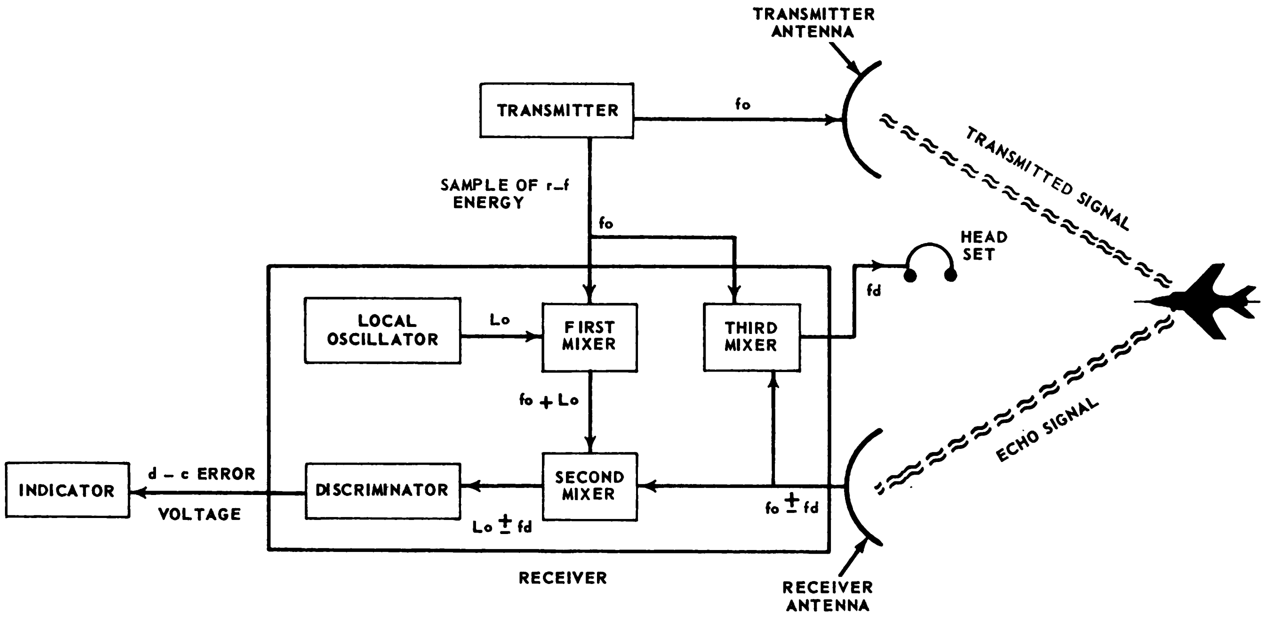

Figure 5-1.—Elementary c-w radar set.

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L_o. The output voltage may be zero, some positive voltage, or some negative voltage. No output is an indication of no Doppler. A positive voltage output is an indication of a Doppler shift in one direction. A negative voltage output is an indication of a Doppler shift in the other direction. The error voltage from the discriminator is applied to an indicating device such as a CRT scope.

In the receiver, the mixers phase-compare their input frequencies. The reference frequencies (f_o and L_o) must be COHERENT. That is, the phase relationship between the two frequencies must be constant with time.

For audio indication of the target the r-f sample is fed into a third mixer where it is beat with echo frequency $f_o \pm f_d$. The output of this mixer is the Doppler frequency. If the Doppler frequency is in the audio range, (approximately 15 to 20,000 cps) an audio device (headset) can be used to indicate the presence of a target.

For an experienced operator, the audio Doppler note of the target contains valuable information. For example:

1. Prop Modulation—Indicates a propeller-drive aircraft, and if it is multi-engine.
2. Turbine whine—Indicates a jet-powered aircraft, and if it is multi-engine.
3. Instantaneous changes in target course and speed.

The information in the audio Doppler is contained in the intensity and pitch of the audio note. The ability of an operator to distinguish these characteristics can be developed by training and practice. The information contained in the audio Doppler of the target will greatly aid in a tactical evaluation of the target.

As you can see, the receiver of the c-w radar is similar in principle to a heterodyne broadcast receiver.

PULSE RADAR METHOD

Let's look at a pulse radar in its simplest form. The transmitter generates a very short pulse of high energy radiofrequency. As the transmitter pulse leaves the antenna, the radar's receiver becomes operative, allowing it to receive and amplify any r-f energy reflected by a target. The time between the transmission of the r-f energy and the echo return is measured electronically and displayed graphically by a CRT. (cathode-ray tube).

Thus the pulse radar can measure range accurately, and does not depend on target's movement for detection. Therefore it can detect both stationary and moving targets.

ELEMENTARY C-W AND PULSE RADAR COMPARED

The c-w echo is changed in frequency by a moving target. This change, as you remember, is called Doppler shift. The Doppler frequency is used for target detection, and to indicate the target's range rate. It is possible, by use of filter circuits, to reject all targets except those traveling at or near a selected velocity. Normally a c-w radar will not detect stationary targets. Since our c-w radar radiates energy continuously, at a constant frequency, there is no reference by which we can measure range directly.

On the other hand, pulsed radar radiates energy at a selected time interval. This interval determines the usable range of the radar. Pulse radar, with its precise measurement of transit time, has a very accurate range measurement capability.

PULSE-DOPPLER RADAR

The pulse-Doppler radar combines the best features of c-w and pulse radar. The pulse-Doppler method uses high frequency c-w, in the form of short bursts, or pulses. The pulse repetition rate (PRR) is much higher than that of a conventional pulse radar, and the pulse length is longer.

A measure of the target's velocity toward or away from the radar can be obtained by means of the Doppler shift. This can be accomplished in the same manner as in c-w radar. We will use a simplified block diagram to show how the pulse-Doppler principle is applied to an elementary radar.

The master oscillator, shown in figure 5-2, provides the basic c-w energy. The output frequency (f_o) must be coherent. A pulse generator is used to chop the c-w energy into pulses for transmission. A target echo contains the transmitted frequency (f_o) and a Doppler frequency component (f_d). To extract the f_d frequency, we feed the output of the receiver and a small sample of the original f_o from the master oscillator into a mixer.

In the mixer the two signals set up a beat frequency. This is similar to the c-w radar, except that now the output of the mixer is pulsed at the PRR. When there is no returned echo (no target in the radar beam) the beat frequency is

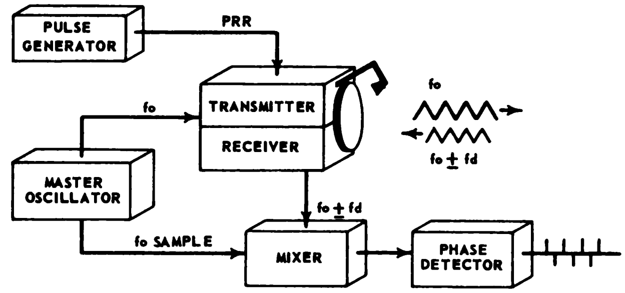


Figure 5-2.—Elementary pulse-Doppler radar set. 55.59

equal to that of the sample of f_o, and is decoupled from the phase detector.

A stationary target's echo has the same frequency as the sample of f_o. Under this condition the magnitude and polarity of the phase detector output will be constant. A stationary target will appear as a fixed signal, which may be either positive or negative, on an A-scope. However, a signal of constant magnitude and polarity can be rejected by the automatic track circuits. From this it can be seen that the pulse-Doppler technique makes it possible to track targets through unrelated noise and clutter that would mask the targets in conventional pulse radar.

For a moving target, the mixer's output varies in magnitude and phase as f_o and $f_o \pm f_d$ go in and out of phase. Each output pulse is an envelope in the form of sine waves whose amplitude will vary at the frequency of the Doppler (beat frequency) signal. These sine waves are the input to the phase detector, whose output is a series of pulses spaced at the PRR. The pulses vary in amplitude and, since they can be either positive or negative, are termed "bipolar." The indication of a moving target on an A-scope has a butterfly-like appearance.

Some pulse-Doppler radar systems do not use the Doppler frequency to obtain a measurement of target's range rate. In these radars the range rate is obtained by measuring the time rate of change of the range gate. This is similar to conventional pulse radars. The Doppler principle is used as a means to operate the radar's receiver with a narrow bandwidth and to reject unwanted targets and noise.

When the target reaches a velocity such that the Doppler frequency is greater than one-half the PRR, the true Doppler frequency can no longer be reproduced, as the sampling rate (PRR) is too low. To avoid this difficulty, the radar must shift to a higher PRR.

We mentioned earlier that the pulse-Doppler radar used a high PRR. This introduces a problem called "blind range." A blind range will occur if a target echo returns to the antenna at the same time another pulse is being transmitted. Since the receiver is closed by the duplexer, the return echo is not permitted to enter the receiver. In other words, the radar does not "see" the target. The radar is therefore blind at this range. At each PRR there are a number of time intervals, at which blind range occurs. These intervals, and hence the blind ranges, vary with the PRR. In the radar, blind range is avoided by circuitry which automatically changes the PRR. During the acquisition phase the PRR is periodically changed.

In our c-w radar we could not measure range because we had no time reference. Pulse-Doppler radar can measure range by using transit time, as in the conventional pulsed radar. However, due to the high PRR, the transmitter will put out several pulses during the time required for a pulse to reach the target and return. To measure range, we must be able to distinguish between these pulses. Each pulse will strike the target and cause a video indication. Therefore it would be possible to use the transmitted time of one pulse as the zero time reference and obtain a false range using the echo of another pulse. To obtain the correct range we must ensure that the zero time reference and the echo return are from the same pulse.

Since the transmitted pulses occur at equally spaced time intervals and the range between pulses is identical, to obtain the correct range the radar range must be set in the correct pulse interval. Range from the designation system can do this. Once set, the radar can gate and track the target at the correct range.

The correct pulse interval can also be determined by the use of different PRRs. Only in the correct pulse interval will the relationship between the rangemark and target video remain constant when the PRR is changed.

ELEMENTS OF A RADAR SET

Gun and missile radar sets now in existence vary greatly in detail and in the function they are designed to accomplish in the field of fire control. They may be very simple or, if more accurate data is required, they may be highly complex and sophisticated. However, the same basic functional sections are found in all radar sets. Thus, any radar set can be visualized to consist of 5 basic sections—synchronizer, transmitter, antenna system, receiver, and indicator.

These sections, shown in figure 5-3, are familiar to you from your study of basic radar. Therefore we will not dwell on them in this course; only a very brief functional description is included here.

RADAR SECTIONS

Synchronizer

The synchronizer is the timing unit. It is the heart of the entire system. It produces trigger pulses which control and coordinate the circuits of the system so that each operates at the correct time. In pulse-modulated systems it governs the number of pulses the transmitter produces in each second (called the pulse repetition frequency (PRF) or pulse repetition rate (PRR). It coordinates the sweep voltage in the indicator tube with the firing of the transmitter, and contains provisions for delaying the beginning of the sweep to give special types of display, such as B, E, A, PPI. The synchronizer contains the circuits which generate the range marker voltages and the trigger pulses which activate the indicator tube when the trace starts to appear on the screen. Pulses supplied by the synchronizer are also used to control associated equipment used with the system. The synchronizer may be known by other terms or names such as keyer or timer.

A missile fire control system may use two separate radar sets to perform the tracking and guidance functions. When sets are grouped in this manner, a separate synchronizer unit (called a master synchronizer) is used to generate timing pulses for each radar set and to coordinate their operation.

Transmitter

The transmitter's purpose is to generate and deliver pulses or continuous waves of r-f energy to the antenna system where it is radiated into space. In gun fire control radars, the generated r-f energy is usually in the X-band, with a frequency range from approximately 8500 to 9600 mc. Missile fire control radars usually operate in the C-band, with a frequency range from approximately 5400 to 6000 mc.

Basically, the transmitter is an r-f oscillator that uses magnetrons, klystrons, or traveling wave tubes to generate microwave energy. The operation of the transmitter is controlled by a signal received from the synchronizer. Strictly speaking, control of the transmitter, such as turning it on and off, is provided by a

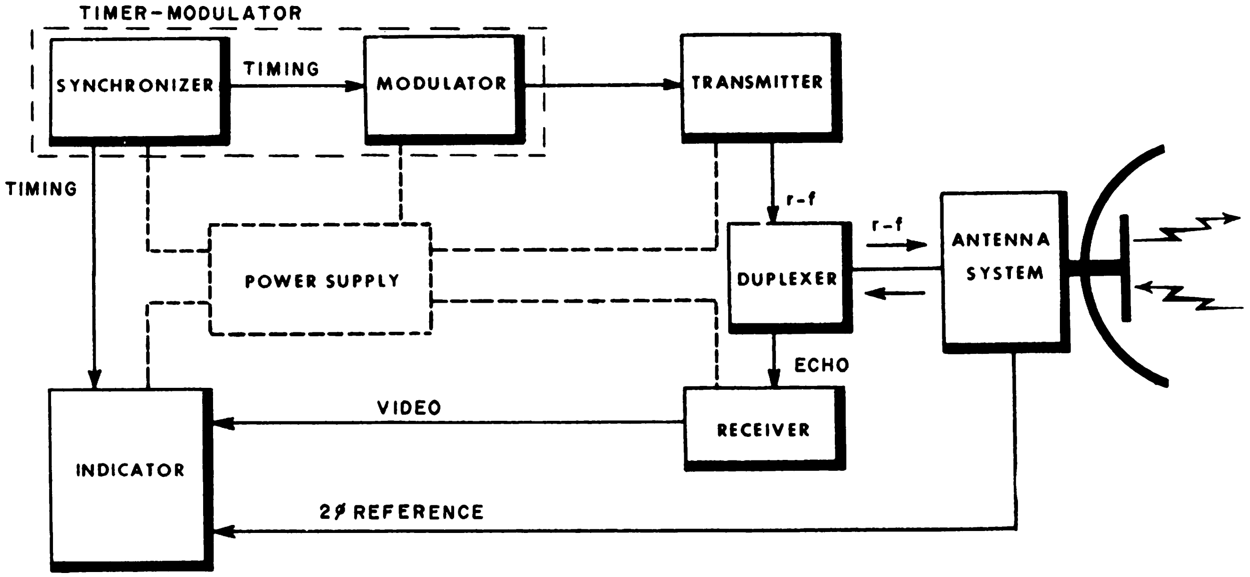


Figure 5-3.—Block diagram of basic radar set.

55.60

section within the transmitter called the modulator. In pulse and pulse-Doppler radars, the modulator is a special circuit designed to supply power to the r-f oscillator when it receives the appropriate signal from the synchronizer. C-w radar transmitters are also controlled by a modulator. The modulator may have another name, but its function is the same as that of any modulator—to superimpose intelligence on the carrier. Many missiles home on energy reflected from a target. The target is usually illuminated by a c-w radar whose carrier is frequency-modulated for identification. Coding the illuminating signal prevents the missile from homing on a target illuminated by a radar other than the missile's companion illuminator.

Antenna System

The antenna system has two general purposes. It radiates microwave energy developed by the transmitter, confining the waves into a narrow beam. In addition, it receives the echo signals from targets and applies them to the receiver. The antenna system consists of waveguides, switching tubes, a reflector for beaming the radiated energy, a mechanism for nutating the feed during operation, and servo units which position the antenna reflector.

Since the same antenna is generally used both for transmitting and receiving, it is necessary to switch it alternately from one component to another. This action is accomplished by the DUPLEXER which consists principally of the TR (transmit-receive) tube and the ATR (anti-TR) tube. These tubes contain gas at a low pressure. Arc-discharges take place in the tubes when the transmitter pulse is applied to the waveguide containing them. The TR tube prevents the transmitted pulse from entering the receiver and damaging the sensitive crystal mixer. When the transmitter is idle, both tubes are de-ionized, and the ATR tube serves to prevent reflected echoes from entering the transmitter, allowing them to flow into the receiver.

Receiver

The receiver is an extremely sensitive superheteordyne containing circuits with bandwidths capable of passing pulses of the type emitted by the transmitter. It is important that the receiver generate as little local noise voltage as possible to avoid masking weak echo pulses.

The signals from the antenna are usually applied first to a crystal mixer where they are mixed with the output of the local oscillator, a reflex klystron tube. The i-f output resulting from the mixing process is then amplified in a number of i-f stages. In most radar receivers the intermediate-frequency value is either 30 or 60 megacycles. A video detector converts the i-f energy into video pulses. After passing through one or more stages of video amplification, the signals are applied to the cathode-ray indicators and range and angle track circuits.

Radar receivers employ automatic frequency control to keep the receiver intermediate frequency from drifting. A typical method is as follows: A portion of the transmitter output is applied to a separate mixer, called the AFC mixer, to which some of the output from the klystron local oscillator is also applied. The AFC mixer develops the difference frequency of the two and applies this signal to a discriminator circuit. The discriminator output voltage is zero when the correct intermediate frequency is produced. But if the receiver local oscillator attempts to drift off frequency, the discriminator produces a d-c voltage which is positive or negative depending on whether the local oscillator frequency is too high or too low. The d-c output of the discriminator is then applied to the klystron local oscillator. This corrects the klystron frequency until it differs from the frequency of the outgoing pulse by the proper amount.

Indicator

The indicator or presentation system accept the radar data such as video pulses, the range-marker voltages, and sawtooth timing waves, and presents them in a visual display on the cathode-ray tubes. An indicator assembly contains the cathode-ray tube and various electronic circuits necessary for presenting the desired information on the CRT. These circuits include video amplifiers, diode clamping tubes, and the controls for adjusting the brilliance of the visual pattern.

Two general types of presentation are used in radar indicators—deflection-modulated and intensity-modulated displays. In the deflection method, the video pulse causes a momentary deflection of the cathode-ray electron beam and produces a pip in the trace to indicate a target echo. In the intensity method, the video signa is applied to the element of the CRT which controls the intensity of the electron beam, and the resulting target image is a bright spot of light. The A-scope is an example of the deflection method, and the PPI is a typical intensity presentation.

Sawtooth timing waves of voltage or current are applied to the deflection circuits of the CRT to produce the time trace or sweep in the pattern. The synchronizing pulse which triggers the modulator and transmitter also serves to coordinate the start of the sweep with the action of the transmitter to make range measurements possible. Target bearing in PPI displays is indicated by synchronizing the position of the sweep line on the CRT with the position of the antenna.

In addition to video pulses, rangemarker pips, and sweep voltages, a square wave pulse is applied to the indicator tube which blanks the beam between sweeps so that retrace lines do not appear on the screen.

MEASUREMENT OF COORDINATES

So far in this chapter we have discussed primarily the basic radar principles of determining the presence of targets. For a fire control radar to be really effective, the range and direction of the target must be known. A complete radar set gives the three coordinates—range, bearing, and elevation—necessary to establish a target's present position. As you know, a line drawn from the origin of a coordinate system to target's position is the line of sight (LOS). The LOS is an essential element in the solution of the fire control problem. It is normally established by a tracking radar.

In the design of a tracking radar, emphasis is placed on good resolution and on extreme accuracy in range and position measurements. To meet these requirements, high carrier frequencies are used, and pulse systems operate at high PRR. Conventional pulse radars transmit short pulses of energy, while pulse Doppler radars send out comparatively long bursts of c-w radiation at a high PRR.

Fire control antennas usually employ parabolic reflectors or microwave lens systems that confine the radiation into narrow "pencil" beams. Antenna systems contain either mechanical or electrical devices which deflect the radiated beams in scanning patterns, such as lobe-switching, spiral scan, and conical scan. The scanning process ensures precision in locating and tracking the target. The receivers in conventional pulse radars have relatively wide bandwidths. Broad-band receivers are necessary so that the steep-sided pulses which contain many harmonics can pass through and be amplified by the receiver stages. On the other hand, Doppler type radar receivers have narrow bandwidths compared to pulse radars.

The operation of fire control radar differs from that of most search radars in that a single object is tracked. During the tracking process the entire attention of the radar is concentrated on one target. The purpose of tracking is to determine continuously the coordinates of range, bearing, and elevation. A block diagram of a basic fire control radar is shown in figure 5-4. Notice the similarity between figures 5-3 and 5-4. The tracking operation consists principally of two basic processes—range tracking and angle tracking.

Ranging System

The ranging system is composed of a group of circuits which not only measure target range and range rate but also control the action of the radar receiver, allowing it to function only during a short time interval when the desired echo is present. The range information is derived by the use of gate pulses which occur after a varying amount of time delay following the transmission of the transmitted pulses. When an echo is received simultaneously with a gate pulse, the range unit automatically locks on the echo and tracks it by adjusting the time of occurrence of the gate to that of the arrival echo. The time delay of the gate pulse then is a measure of the target's range.

Sections of the receiver are disabled and no output is produced until the range unit permits the passage of the desired signal by applying an enabling voltage to the receiver circuits. By keeping the receiver inoperative except for this brief time interval, echoes from objects at ranges different from that of the principal target are excluded from the range servocontrol circuits. Also, unwanted receptions from enemy jamming transmitters are largely prevented, as well as undesirable reflections from the sea or shore.

Angle Tracking System

The angle tracking system keeps the radar antenna pointed at the target to derive information concerning the angles of bearing and elevation. In fire control radar, angle tracking, as

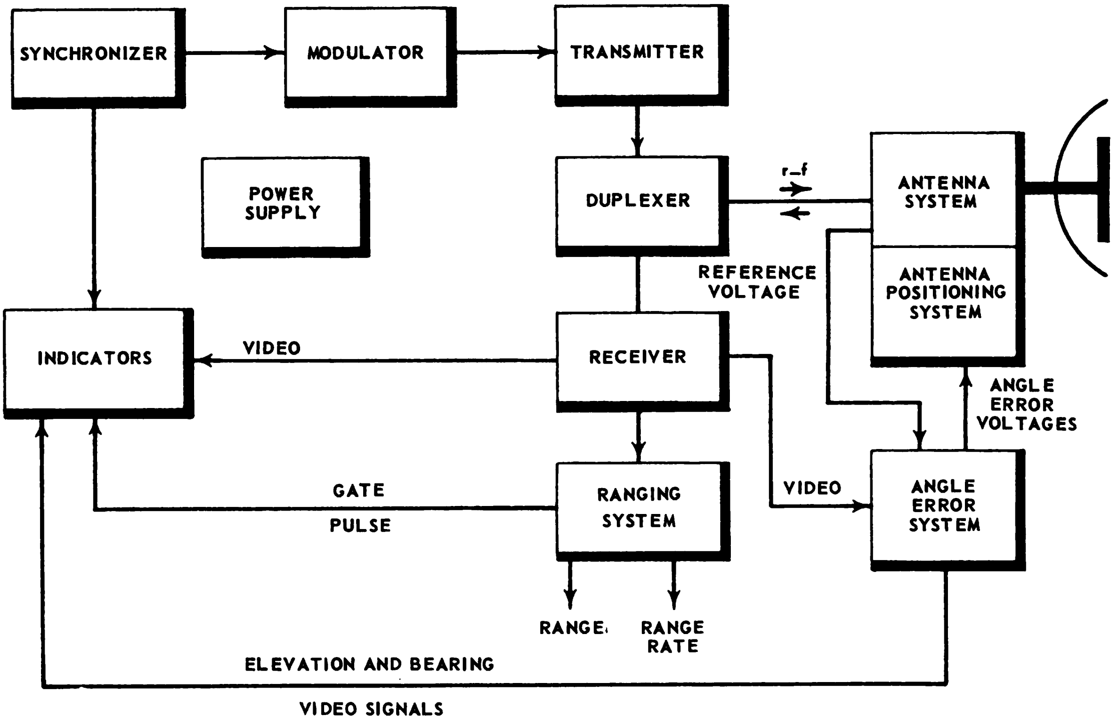


Figure 5-4.—Block diagram of basic fire control radar system. 55.61

well as range tracking is usually accomplished automatically. Generally, the radar beam is swept over the area containing the target in such a way that the returning echoes vary in amplitude with the position of the object with respect to the axes of the radar beam. The target echoes determine the receiver output, which is converted into control voltages proportional to the error in the aim of the antenna. The error voltages are then applied to servomechanisms which adjust the direction of the antenna to cause the system to lock on the target and follow it accurately.

The techniques of range and angle measurement by radar are of fundamental importance in all aspects of fire control. To make clear the methods by which the angular error signals are derived during the process of angle tracking, it is necessary to consider the actions of the antenna system in shaping and directing the required narrow beam, and also the manner in which the energy is scanned over the target area.

ANTENNA ASSEMBLIES AND BEAM SCANNING

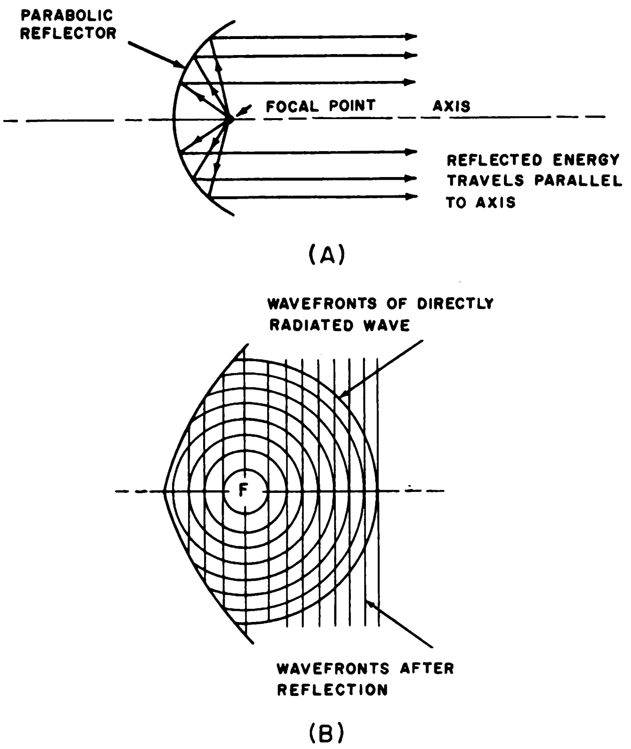
In the operation of the radar as a tracking device, the antenna system performs several important functions. It contains a metallic reflector and a feed device for transmitting and concentrating microwave energy in narrow beams, and for receiving echoes from certain directions. Some antenna systems use a lens instead of a reflector to form a beam.

Since the antenna axis, also referred to as the boresight axis or line, is the principal reference line in determining target location, the antenna is usually stabilized in space so that motions of the ship will not affect the movement of the beam. The antenna system may include a device for deflecting the beam in a regular motion to scan the target area.

PARABOLIC REFLECTOR

The type of reflector generally employed in gun fire control radars is the parabolic disk. It is similar in appearance to the reflector used in automobile headlights. One of the important advantages of radar operation in the microwave region of the electromagnetic spectrum is that microwaves have properties and characteristics similar to those of light. This permits the use of well known optical design techniques.

The action of the reflecting surface of the reflector is a result of its parabolic shape and


PARABOLIC REFLECTOR
FOCAL POINT
AXIS
REFLECTED ENERGY TRAVELS PARALLEL TO AXIS
(A)
WAVEFRONTS OF DIRECTLY RADIATED WAVE
F
WAVEFRONTS AFTER REFLECTION
(B)

1.49:25.226

Figure 5-5.—Principle of parabolic reflector.

the fact that the rays striking and reflecting from the metallic surface make equal angles with the surface at the point of reflection. This action is illustrated in figure 5-5. In A of the figure, consider that the focal point is a feedhorn radiator and is a point source of energy. As you learned in Fire Control Technician 3, NavPers 10173-A, electromagnetic energy is emitted from a point source in spherical waves like ripples that fan out from a pebble thrown into a pond of still water. The primary purpose of the parabolic reflector is to change the spherical wavefronts of the radiated energy into flat (plane) waves and focus them into a circular beam. Part B of figure 5-5 shows spherical wavefronts coming from a radiating feedhorn at the focal point of a parabolic reflector. As the waves strike the reflector they are straightened and concentrated into a narrow circular beam of energy containing parallel flat wavefronts.

When the radar is receiving reflected energy, the incoming rays are concentrated and focused on the feedhorn only when they enter the dish in perfectly parallel rays as shown in B of figure 5-5. The waves reflected from the target, under ideal conditions, will be parallel if they were transmitted in this form. Therefore, we can state that in any antenna system the transmitting and receiving patterns are essentially the same. For this reason one antenna can be used for transmission and reception. The parabolic reflector produces a "pencil beam" in which most of the energy is confined to a small cone of nearly circular cross section. The concentration of the energy into a beam increases the amount of radiation illuminating a target.

MICROWAVE LENSES

Another device used to form microwave energy into a narrow beam is the lens. It too takes advantage of the similarity of light and microwaves. A lens is a structure substantially transparent to microwaves but which inserts a phase change over the cross section of the exit side of the lens to make the microwaves converge or diverge. The lens is placed in front of a point source of r-f energy, such as a feedhorn. The feedhorn is located at the focal point of the lens. It radiates spherical waves which are concentrated into a beam as they pass through the lens.

The explanation of microwave lenses can be better understood if we first consider a little background information. Then we will see that the microwave lens and its principles of operation are not strangers to us. Microwaves are similar to light in that both (like many other types of energy) travel in waveform. Consequently, both obey the physical laws of wave transmission. Although the primary purpose of an r-f transmission line is to guide the transfer of energy from one place to another, in so doing the transmission line has other characteristics which may be useful in certain cases. For example, if a voltage is applied to the input terminals of a line, a definite amount of time passes before the voltage appears at the output terminal. In other words, the line has the ability to delay the transmission of voltages and currents. The time delay is determined by the length of the line and its characteristics, R, L, and C. The time delay of a transmission line has many applications in radar timing. The artificial transmission lines used in radar employ this factor.

However, there is nothing in the physical laws of microwave transmission that says we must have a material conductor. The same laws apply to propagation of r-f waves in air or in a vacuum. The velocity of wave propagation is determined by the characteristics of the medium through which it travels.

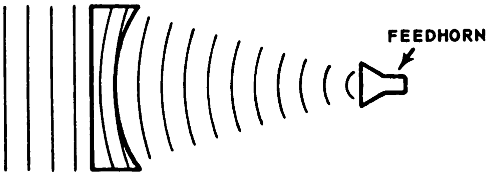


Figure 5-6.—Waveguide (acceleration) type microwave lens. 55.62

Microwave lenses are of two types. One is the waveguide, or conducting, type shown in figure 5-6. This type accelerates wave transmission as it passes through the lens. It consists of flat metal strips placed parallel to the electric field of the wave and spaced slightly in excess of one-half of a wavelength. To the wave these strips look like waveguides with each hypothetical waveguide having a dimension in a direction perpendicular to the electric field corresponding to the spacing between the parallel strips. The velocity of phase propagation of a wave is greater in a waveguide than in air. Thus since the lens is concave, the outer portions of the transmitted spherical wave are accelerated for a longer interval of time than the inner portion. The spherical waves will emerge at the exit side of the lens (lens aperture) as flat-fronted parallel waves. The waveguide type lens is frequency sensitive.

The other type lens is the dielectric, or metallic delay lens, shown in figure 5-7. The delay lens, as its name implies, slows down the phase propagation as the wave passes through the lens. This lens is convex, and consists of dielectric material. The delay in the phase of the wave passing through the lens is determined by the dielectric constant or refractive index of the material. In most cases, artificial dielectrics consisting of conducting rods or spheres that are small compared to the wavelength are used. Artificial dielectrics, or conducting insulators, used in r-f transmission systems are covered in Basic Electronics, NavPers 10087-A. In this case the inner portion of the transmitted wave is decelerated for a longer interval of time than the outer portions.

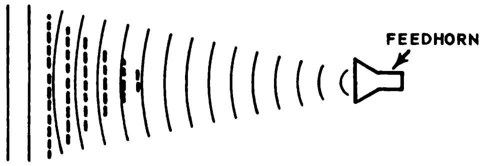


Figure 5-7.—Metal strip (delay) type microwave lens. 55.63

In a lens antenna the exit side of the lens can be regarded as an aperture across which there is a field distribution. This field acts as a source of radiation just as fields across the mouth of a reflector or horn. For a returning echo the reverse effects take place in the lens.

It can be seen that the reflector uses the law of reflection while the lens uses the law of refraction. The rear feed arrangement of the lens antenna eliminates spillover radiation in the backward direction. Also, this arrangement puts the radiator out of the path of the beam, thus reducing shadows.

SCANNING

In addition to radiating and focusing energy into a narrow circular beam, the antenna system must provide a means for searching for a target and for determining its position. This process is called scanning or lobing. Lobing can be divided into two broad categories—(1) sequential lobing and (2) simultaneous lobing. Examples of sequential lobing are conical scanning and lobe switching. Simultaneous lobing is best illustrated by a fairly recent lobing technique called monopulse. We shall discuss this method in considerable detail later. But first a brief review of more familiar scanning processes is in order so that you can see how and why monopulsing was developed.

Single-Lobe System

The simplest method of obtaining direction is to point a single narrow beam (lobe) of radar energy at a target. A radar antenna may be mounted so that it can sweep, or scan, in any direction. But for the sake of simplicity, let us restrict the antenna's motion to the horizontal plane. This allows the radar to determine target bearing only, but the same basic principle applies to finding target elevation.

When a target is detected in the beam as indicated in A of figure 5-8, the operator trains the antenna until the height of the echo on his A-scope is maximum. At this point, the target

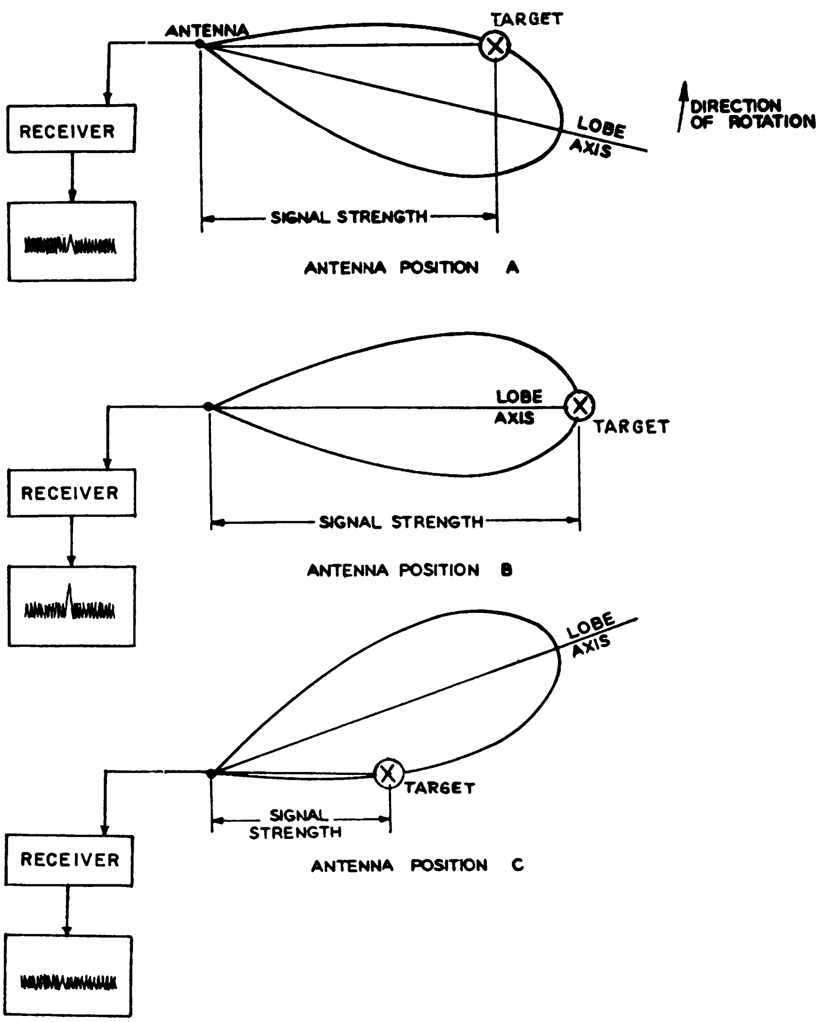


Figure 5-8.—Relation between beam axis and target bearing in a single-lobe system. 20.284

is on the beam axis as shown in B of figure 5-8. If the antenna is moved to either side, as in figure 5-10 A and C, the echo decreases in amplitude. Figure 5-8 illustrates the relative strength of the echoes for different positions of the target with respect to the beam axis. A small angle on either side of the axis does not make much difference in signal amplitude, but when the target lies toward the outer edge of the beam a slight change makes a great difference.

On the A-scope the target begins to appear when the edge of the beam touches it. The indication is strongest as the beam axis crosses the target. However, the target continues to appear on the scope as long as any part of the beam touches it. Therefore, if the beam is wide the target appears for a long period of time on the scope.

You can see that the degree of accuracy which can be obtained from a single-lobe system depends on beam width and on the operator's ability to determine the point of maximum signal amplitude as he scans the antenna. Keep in mind that the operator is comparing successive signal amplitudes all the while he is moving the antenna. Comparison of signal characteristics—in this case amplitude—is the basis of all types of lobing. The case in point also illustrates the fact that he compares the amplitudes of returned echoes in a sequence. Thus a single lobe system is the simplest form of sequential lobing.

Double-Lobe System

The double-lobe system multiplies by several times the accuracy obtainable with a single-lobe system. The double-lobe system employs two overlapping beams. For ease of illustration, assume that two antennas are used side by side. Two signals are obtained when the beams cross a target, one from each beam. On the radarscope they appear either side by side or back to back. The two signals are the same amplitude only when the target is on the line of intersection of the two beams, as in figure 5-9. The operator rotates the antennas until the signals are matched in amplitude. At this point, he knows that the target lies on the LINE OF INTERSECTION of the two beams. The target is located on the basis of returns from the side of each lobe, where a small change in position results in a large change in signal amplitude. Therefore, if the antennas are moved in either direction away from this angle, one of the signals increases greatly in amplitude and the other decreases. You can see that a greater degree of accuracy can be obtained in this way.

Besides greater accuracy, the double-lobe system has another advantage over the single-lobe system. By watching to see which of the two signals increases in amplitude as the antenna is rotated a few degrees, the operator can tell the direction the antenna must be moved to reach the on-target position.

Lobe Switching

In the discussion of lobing so far, we have moved the antenna or antennas to perform lobing. This is too crude a method for modern fire control purposes. Some World War II fire control radars overcame this problem by using one antenna and a motor drive device to switch lobes without moving the antenna. When this technique, called lobe switching, is used, lobing takes place at a rapid rate, thus more signal amplitude comparisons can be made in a given time.

Briefly, this is how the system works to provide target direction in the horizontal plane. The antenna produces two beams, one at a time, switching rapidly from one to the other. The feed is alternately changed in phase to create the double-lobe effect. This phase shifting is done mechanically or electrically by switching feed lines. This eliminates the need for two antennas and two receivers. The directions of the two lobes differ by a small angle equal to about one beam width. Signals are returned to the radar as each beam strikes the target. When the two echoes are compared, the strength of one with respect to the other depends upon the position of the target in relation to the antenna direction, as shown in figure 5-10.

The returning signals are equal in strength only when the reflecting object lies on the line bisecting the angle of intersection of the two lobes. If the target is situated on either side of this line, the echoes differ in amplitude in such a way as to indicate whether it is to the left or to the right of the antenna direction. The two signals are compared visually, and the radar operator moves his train handwheels to adjust the antenna direction for equal amplitudes of the received signals. To track an air target, a second pair of beams is used to determine target elevation. These beams are lobed in a vertical plane.

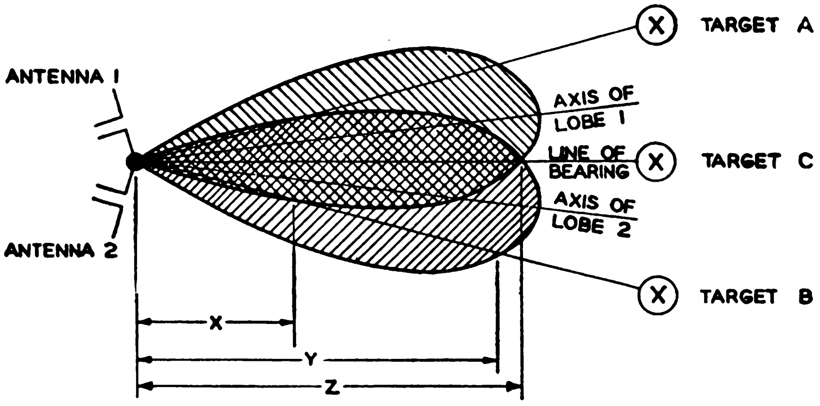


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Figure 5-9.—Relation between axis of intersection and target bearing in a double-lobe system.

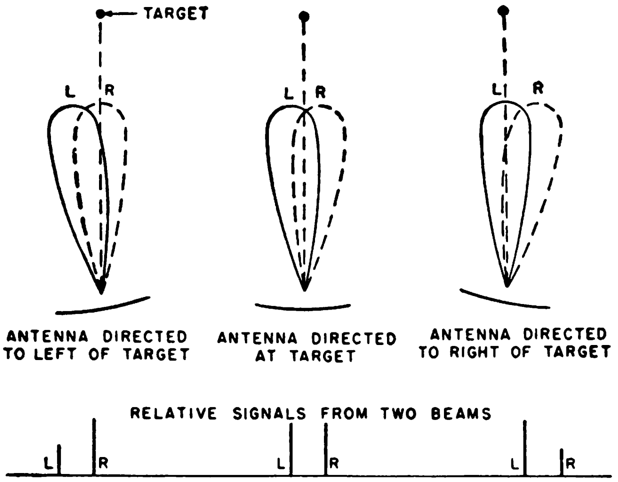

TARGET
L
R
L
R
L
R
ANTENNA DIRECTED TO LEFT OF TARGET
ANTENNA DIRECTED AT TARGET
ANTENNA DIRECTED TO RIGHT OF TARGET
RELATIVE SIGNALS FROM TWO BEAMS
L
R
L
R
L
R

Figure 5-10.—Lobe switching. 55.64

Conical Scan

In the two systems just described the operator performs the signal comparison process. In addition, he must control the antenna to track a moving target. With fixed or slow-moving targets he can, with practice, perform these functions efficiently; however, when a target flies at a high speed, it is almost impossible for a human being to do all the functions required for precise target tracking and direction finding. Also, when lobe switching is used, the process itself introduces mechanical and electrical problems which reduce the reliability and tracking accuracy of the radar. The limitations just mentioned spurred the development of newer techniques to be used with automatic tracking circuits. Conical scanning was the result of this development program. It provides the three-dimensional sequential lobing necessary to determine a target's position and to track it with high precision.

In conical scan the radiated beam is deflected by the antenna to produce a rapidly rotating beam that forms a small cone. The apex (point or tip) of the cone is located at the center of the antenna as shown in figure 5-11. Conical scanning is accomplished by nutating the feed (either horn or dipole) while the reflector remains fixed. The reflector dish is mounted exactly in the center of nutation. This assembly is shown in figure 5-12. As a result of the nutation of the feed, the beam spins in space in the manner indicated in the figure.

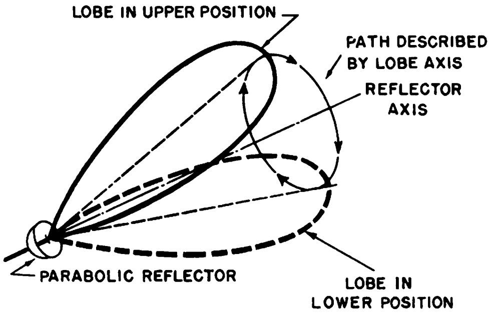
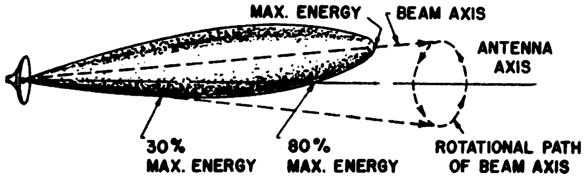


Figure 5-11.—Conical scanning. 33.113



55.65
Figure 5-12.—Antenna beam with conical scan.

Also shown in the figure, during automatic tracking the beam points at an angle of a few degrees with respect to the antenna axis. A target located exactly on the antenna axis continuously receives a constant amount of the radiation, in this case about 80 percent of it. However, a target situated away from the axis receives radiation that varies in strength from 100 percent of maximum to less than 30 percent, depending on its displacement from the line along which the antenna is pointing. This is shown more clearly in figure 5-13, in which the return signals from a target that is 1 1/2° off the antenna axis (fig. 5-13A) are contrasted with the echoes from a target on the axis (fig. 5-13B).

The axis of the antenna does not change appreciably during the time required for several spins of the beam; hence the direction of the lobe after one-half revolution changes from the upper position shown in figure 5-13 to that shown in the lower position. As the beam rotates between these extreme positions, the echo signals vary gradually in strength, as shown in figure 5-14, so that the returned pulses are amplitude-modulated in proportion to the displacement of the target from the antenna axis. The figure shows only eight echo signals per revolution for convenience, but in an actual case many more

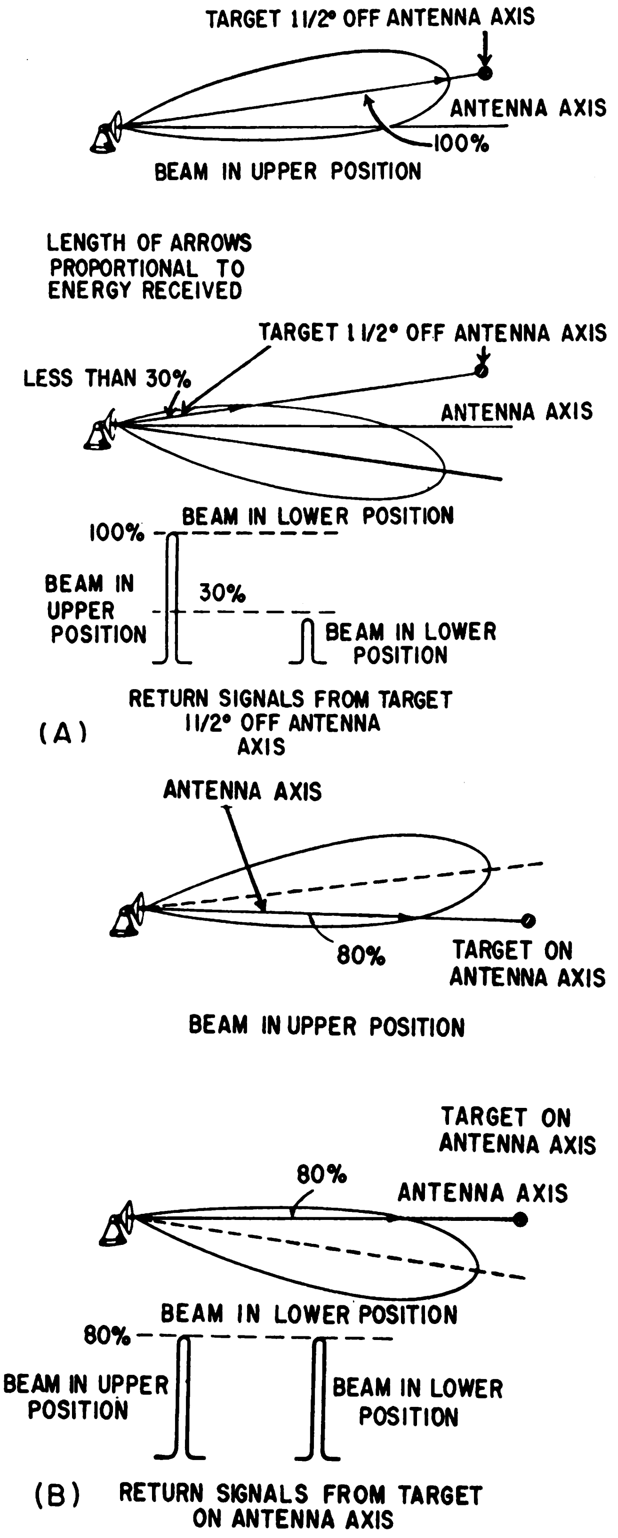


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Figure 5-13.—Echo signals with conical scan.

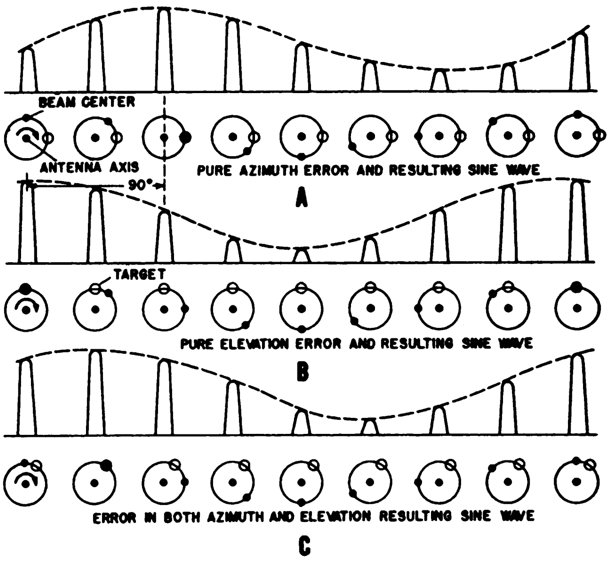
BEAM CENTER
ANTENNA AXIS
90°
PURE AZIMUTH ERROR AND RESULTING SINE WAVE
A
TARGET
PURE ELEVATION ERROR AND RESULTING SINE WAVE
B
ERROR IN BOTH AZIMUTH AND ELEVATION RESULTING SINE WAVE
C

Figure 5-14.—Signals produced by bearing and elevation errors. 55.67

are present, the number for each revolution being determined by the ratio of the pulse repetition frequency to the rate of rotation of the beam.

The azimuth and elevation angles of the target with respect to the antenna axis are indicated by the phase of the variations in returned signal strength, as indicated in figure 5-14. In A of the figure is shown the signal resulting from an error in azimuth only; while that produced by an error in elevation alone is shown in B. By comparing the two diagrams, it can be seen that the variation representing azimuth error is displaced in phase by 90° from a signal produced by a pure elevation error. The error signal resulting from a combination of azimuth and elevation errors is shown in C of the figure, in which the variation in amplitude reaches a maximum value somewhere between the moments of maximum for pure azimuth or pure elevation errors. Any other position of the target results in a similar error signal, the phase of which is determined by the direction of the azimuth and elevation errors present.

When the axis of the antenna points directly at the target, the echo pulses are all of equal amplitude, as shown in B of figure 5-13. In automatic tracking, the error control voltages are applied to servomechanisms which position the antenna so as to zero the error signals and maintain the antenna aim fixed on the target.

Conical scanning is the most common sequential lobing technique used in shipboard gun or missile fire control radars. For the moment let us focus our attention on conical scanning as applied to the older gun fire control radars. If you are a Missile Fire Control Technician, don't skip what follows because the subject to be treated can be applied to some missile radars though to a lesser degree.

There are certain limitations to the angle tracking accuracy in ANY sequential lobing system. You have probably seen the results of this limitation in the form of jitter while tracking targets in automatic. Some of the jitter is caused by inherent noise and lag in the antenna positioning servoloop. But a portion of the jitter is produced by the target echo input to the receiver. Target return signals contain several components of noise; the major part of this noise is caused by pulse-to-pulse fading of the return echoes. Fading occurs at a rapid rate and pulse amplitudes vary from pulse to pulse. This phenomenon is also called scintillation. It is caused, primarily by a change in the target's course or attitude. As the target pitches, rolls, and yaws it presents a changing cross section to the radiated beam. Thus one reflected pulse may have a strong signal while the following pulse may be weaker or stronger than the first. The effect of scintillation is to modulate the input signal to the receiver at the scan rate. After detection, the signal is passed on to the angle tracking loop and shows up as tracking jitter. Smoothing circuits are provided to average out these unwanted modulations over a period of time. For example, the GFCS Mk 56 has a smoothing circuit between the phase detector and gyro precession circuits for this very purpose.

MONOPULSE

The methods of scanning that you have just studied are sometimes called sequential lobing, because target information must be gathered from a series or sequence of pulses. Another scanning technique, called monopulse or simultaneous lobing, can obtain information on target range, bearing, and elevation from a single pulse.

For target tracking, the radar discussed here produces a narrow circular beam of pulsed r-f energy at a high pulse repetition rate. Each pulse is divided into four signals which are equal in amplitude and phase. The four signals are radiated at the same time from each of four feed horns grouped in a cluster as shown in figure 5-15. The radiated energy is focused into a beam by a microwave lens of the type mentioned previously. Energy reflected from targets is refocused by the lens into the feedhorns. The amount of the total energy received by each horn will vary depending on the position of the target relative to the beam axis. This is illustrated in figure 5-16 for four targets at different positions with respect to the beam axis. Be sure to notice, and remember, that a phase inversion takes place at the microwave lens similar to the image inversion in an optical system.

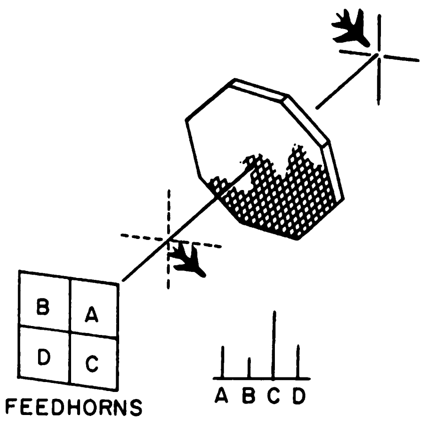

Figure 5-15.—Monopulse technique. 55.68

The amplitude of returned signals received by each horn is continuously compared with those received in the other horns, and error signals are generated which indicate the relative position of the target with respect to the axis of the beam. Angle servocircuits receive these error signals and correct the position of the radar beam to keep the beam axis on target.

The traverse (train) signal is made up of signals from horns A and C added and from horns B and D added. By waveguide design the sum of B and D is made 180° out of phase with the sum A and C. These two are combined and the traverse signal is the difference of (A + C) - (B + D). Since the horns are positioned as shown in figure 5-16 the relative amplitudes of the horn signals give an indication of the magnitude of the traverse error. The elevation signal consists of the signals from horns C and D added 180° out of phase with A and B, i.e., (A + B) - (C + D). The sum or range signal is composed of signals from all four feedhorns added together in phase. The range signal is also used as a phase reference for the traverse and elevation error signals.

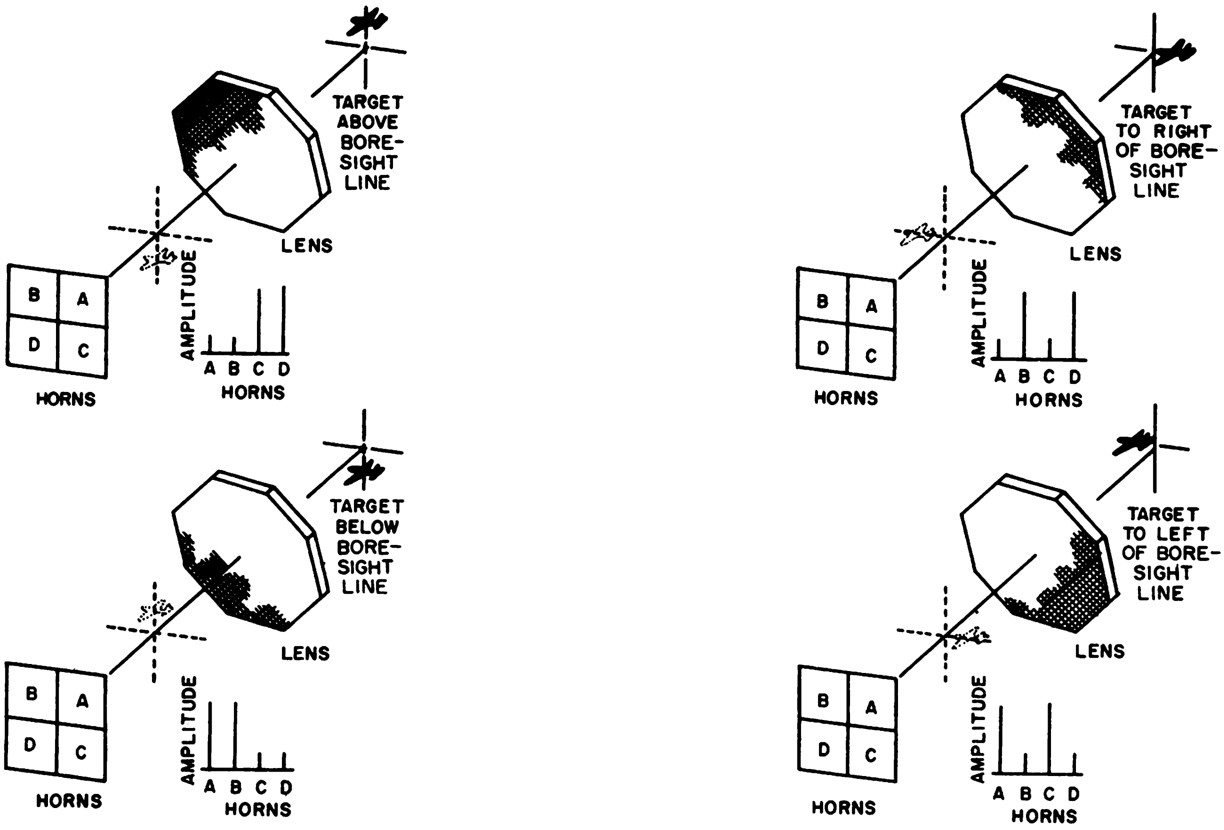

Figure 5-16.—Amplitude changes of received energy with target position. 55.69

The traverse and elevation error signals are compared in the radar receiver with the range or reference signal. The output of the receiver may be positive or negative pulses, the amplitude of which is proportional to the angle between the boresight (beam) axis and a line drawn to the target. The polarity of the output pulses indicates whether the target is above or below, to the right or to the left of the boresight axis. Of course, if the target is directly on the boresight line, the output of the receiver is zero, and no angle tracking error is produced.

CHAPTER 6

RADAR TESTING TECHNIQUES

In this chapter you will learn about the operation and testing of the functional sections of a basic radar set. The principles of operation and the testing techniques discussed here apply generally to any radar set, regardless of its application. Therefore, what you learn in the following pages can be applied to the maintenance of a gun or missile radar.

SYNCHRONIZER

You probably recall from chapter 5 that the function of the synchronizer is to produce voltage pulses for timing the operation of the units of a radar. The synchronizer establishes a TIME REFERENCE for the radar set. In other words, the synchronizer sets up the order or sequence in which the units of the radar operate.

The pulses produced by the synchronizer trigger into operation the modulator, the receiver, the indicator system, and the automatic tracking circuits. Some of the timing pulses determine not only when a unit is made to operate but how long the unit operates after it is triggered. A timing pulse that sets a tube or circuit into operation is called a TRIGGER or SYNC pulse. A timing pulse that not only sets a unit into operation but also establishes the length of time it operates is called a GATE pulse.

TYPES OF TIMING PULSES

Figure 6-1 shows some sample outputs of a typical synchronizer. Notice the time relationship between the outputs. The trigger pulse to the modulator (part A of figure 6-1) starts the high power pulse to the r-f oscillator. Therefore, the r-f transmitted pulse (part B of figure 6-1) occurs at the same time as the modulator trigger pulse. Note that the transmitted pulse is not an output of the synchronizer. It is shown here to indicate the time relationship of the other pulses to the transmitted pulse. In some of the earlier fire control radars, it is desirable to have the receiver operate only for a part of the time between transmitter pulses. This permits the operator to track only one target and prevents him from being confused by a large number of return echoes. The pulse that is used to activate the receiver is called a GATE pulse, as shown in figure 6-1C. The gate pulse turns on the receiver just after the main transmitted pulse ends. This prevents the receiver from being damaged or blocked by the transmitted pulse. In modern radar receivers the TR box and sensitivity-time-control (STC) circuits protect the receiver adequately, and long gate pulses are seldom used.

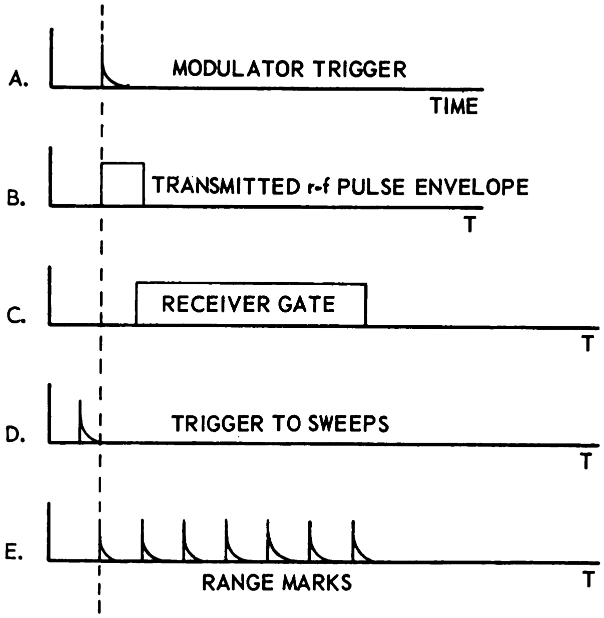

Figure 6-1.—Outputs of a typical synchronizer system. 55.70

In figure 6-1D, the trigger to the indicator occurs slightly ahead of the transmitter trigger. This occurs only in radars in which the indicator sweep requires a short interval in which to start and become linear. In some radars, however, the trigger to the indicator is delayed by a delay line so that the indicator sweep can begin exactly at the same instant that the pulse leaves the antenna.

The rangemarks shown in figure 6-1E occur at regular intervals after the transmitted pulse. The marker pips are fed to the indicator tube, where they cause small deflections of the sweep at intervals known to the operator. The deflections of the sweep represent a range interval in yards. Thus, the operator can read the approximate range to the target. In B-scope and E-scope presentations the range marks are intensified parts of the trace, rather than deflections.

Accurate knowledge of target range is a most important requirement of any radar set. Circuits which produce movable or delayed marks are the basis for highly accurate range measurement. These movable markers are identical to the range markers shown in figure 6-1E, and are generated in the synchronizer. Movable triggers are also required for automatic tracking. Among the more important movable triggers are the Early and Late tracking gates, as they are sometimes called. These gates are used for detecting and gating a target in range, and are calibrated so that they occur at a time corresponding to the range on the range dials.

SYNCHRONIZER TROUBLESHOOTING AND ALIGNMENT

The proper operation of the synchronizer is extremely important to the effectiveness of a radar. Therefore, you must keep a regular check of synchronizer operation. You can make this check with a synchroscope, which is simply an oscilloscope whose sweep is triggered by each incoming sync pulse, as contrasted with the continuous sawtooth sweep provided by the oscilloscope. You can compare the waveforms at test points within the synchronizer with those shown as being normal in the appropriate POMSEE book or the radar's OP. If possible, use the best scope specified in these publications.

Test equipment is ually available, but in an emergency you can use a set of radio earphones to tell whether or not a sync trigger is at a test point. It is best, though not necessary, to attach a 0.5μ f capacitor in series with the phone jack to keep any stray direct current from damaging the earphones. Attach the earphones to the test jack and listen for the trigger signals. They occur at audiofrequencies and should produce a hum or whistle in the phones. Be sure, however, that you stay out of high voltage circuits during this test.

The synchronizer is subject to a few unusual troubles. Some of the most common troubles are: (1) aging or burned-out tubes, (2) shorted sync cables or terminal connections, and (3) in radars where the synchronizer is an integral part of the transmitter, a defective capacitor in the delay lines or a shorted sync winding in the pulse transformer.

When testing a synchronizer, one of the first things you should look for is the main or reference triggers. Look in the OP provided for your radar. Test points are listed in the book or shown on troubleshooting diagrams. These test points will help you to determine whether the main timing pulse is present. After locating the proper test points, you should use the test scope recommended by the OP to see whether the pulse is of the correct amplitude and shape, as shown in the book.

Tubes that are weak cause the synchronizer to become completely disabled, or the timing pulse to decrease in amplitude or become erratic. First, if you can, determine from the operation of the radar and radarscopes which units are affected. If you can isolate the defective unit, your work will be simplified.

However, if you cannot isolate the trouble to a particular unit, then trace the timing signal from the synchronizer on through the circuits until you locate the point where the signal disappears or becomes faulty. Your radar maintenance publication shows you the check points for attaching the test scope and the way the pulse should look at each test point.

Often you can isolate the defective unit by a visual inspection of the radarscope. If this inspection does not enable you to determine which unit is defective, you should examine both the input and output signals of each unit by means of a test scope until you find the defective unit. At this point a visual inspection may indicate a defective tube. (Glass tubes sometimes show a blue glow in the space within the envelope when they are gassy; cold or dark tubes indicate a burned-out heater.) Tubes that look defective should be replaced and the equipment tested again. If this does not correct the fault, proceed to trace the signal through the defective unit. Your radar OP or POMSEE book shows you the test points and the appearance of the pulse at each point. These test points are usually provided at the input and output of one or more stages, and it is therefore possible to determine the defective stage or stages. Now test the tubes in the stages involved, preferably by substituting tubes which have been checked previously in the equipment. If a tube is not at fault the circuit components should be examined, first visually and then by checking voltages and resistances until the defect is found and remedied.

TRANSMITTER

Most radar transmitters are made up of two functional sections—the modulator and the r-f oscillator. The term modulator is used in this book to describe the circuits that generate and shape the high powered d-c pulse that is applied to the r-f oscillator. The oscillator may be one of several devices, such as a magnetron, klystron, or traveling wave tube. Now let us take a closer look at these two sections, to see how they operate and how they are tested.

BLOCK DIAGRAM OF THE MODULATOR

Figure 6-2 shows a block diagram of a typical modulator. The modulator consists of three main parts—the charging device, the pulse-forming network, and the switching device. The power supply, load, and trigger circuits are auxiliary parts of the modulator. In most radars, after the network is switched, the rectangular output pulse is passed through a special pulse transformer. The output from the secondary of the transformer is fed to the cathode of the r-f oscillator. (In this discussion the r-f oscillator is a magnetron.) In a few radars, the output from the switching device is passed directly to the magnetron cathode.

Suppose you follow the modulator in figure 6-2 through one pulse cycle. The pulse-forming network (PFN) is connected through the charging device to the high voltage supply. The network charges resonantly during the period when the switch is open. In other words, a sudden flow of current through the charging device produces a surge of voltage that swings far above the supply voltage. The PFN charges to the upper limit of this surge. The negative part of the oscillation started by this surge is damped out by a diode. If the power that charges the network is from a d-c supply, the network becomes charged to about twice the supply voltage.

When the PFN reaches its maximum charge, it is ready to be switched, or keyed. In other words, the network is ready to be discharged through the load to ground. The exact time that the PFN is switched is determined by a trigger voltage from the synchronizer.

When the switch closes, the PFN discharges at a rate determined by the LC constants in the network. The resulting high amplitude d-c pulse is applied through the primary of the pulse transformer. The sudden pulse in the transformer primary induces a pulse of extremely high voltage in the secondary. The secondary winding is connected directly to the cathode of the high powered r-f oscillator. The powerful negative pulse at the cathode of the magnetron oscillator causes it to oscillate for the duration of the pulse.

PULSE-FORMING NETWORK

The pulse-forming network consists of a series of coils and capacitors in an arrangement like that shown in figure 6-3. There are other

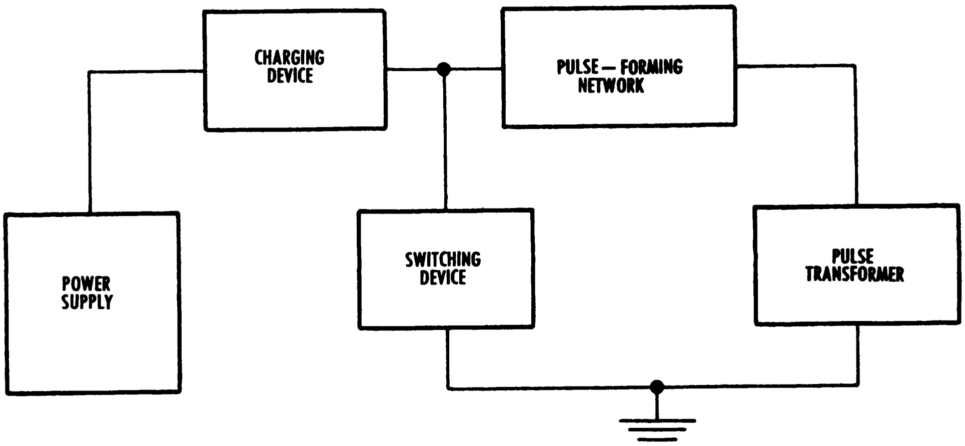

Figure 6-2.—Block diagram of a typical modulator.

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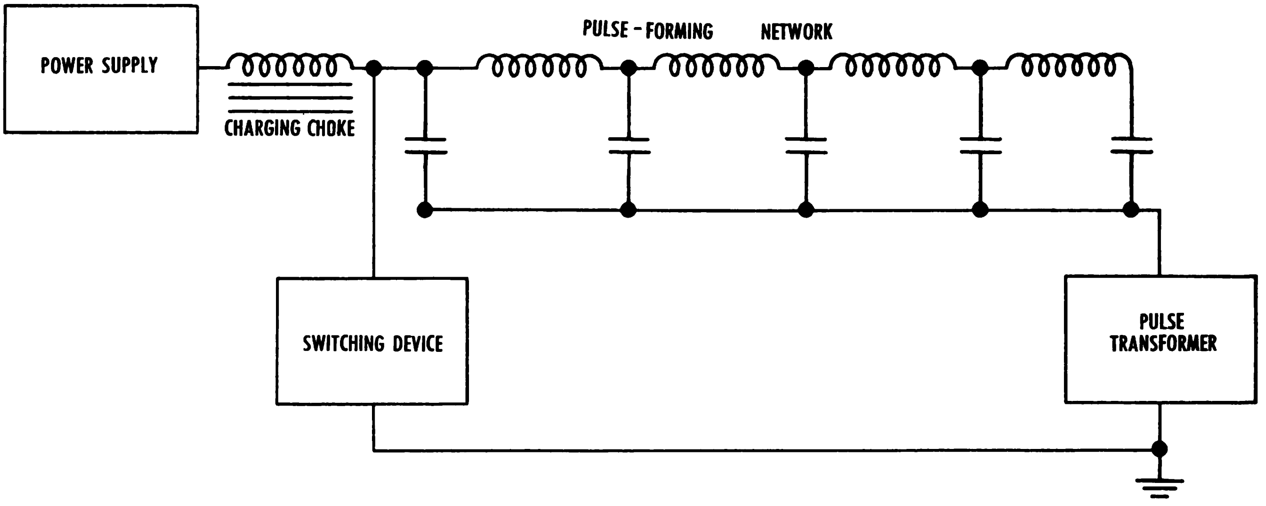

Figure 6-3.—Schematic diagram of a typical pulse-forming network and charging choke. 55.72

arrangements for the elements in the PFN, but the arrangement shown is common. Most pulse-forming networks have a CHARGING CHOKE in series with the input. The choke (1) is series resonant with the line and (2) isolates the power supply from the switching device during discharge. The LC constants in the network are carefully selected to provide a pulse of the proper shape and duration. The coils and capacitors must be rated to withstand the high voltages and currents they encounter in building up the high powered pulse.

The PFN and charging choke are designed so that their combined impedance matches the output load as nearly as possible when the network is switched. The output line therefore appears as an infinitely long transmission line when the switch is closed. This reduces reflections in the charging circuit during the discharge interval. During the charging time, however, when the switch is open, the network is resonant. During the time when the network is resonant, it can be charged above the supply voltage.

The output voltage pulse from a d-c resonant charging network is about half the voltage to which the network is charged because the line impedance and load impedance are equal. Since the network has losses and is charged to nearly twice the supply voltage, and the output pulse voltage is half the network charge, the usable voltage in the output pulse is only 0.9 of the supply voltage.

SWITCHING DEVICES

A switching device forms a series circuit with the pulse-forming network and the load. Whereas the PFN determines the shape and duration of the oscillator pulse, the switching device establishes the time of each pulse. Thus, the rate at which the switching device fires is the pulse-repetition frequency of the radar. A trigger pulse (from the synchronizer) determines the exact time when the switch fires and discharges the pulse-forming network.

Assume that you connect a hand key in series with the pulse-forming network shown in figure 6-3. Each time you depress the key, the network discharges. While the key is open, the network can charge again. This is the way that the switch works. However, you would have a hard time depressing a key by hand 1000 times a second or more. Therefore, some electronic device for switching must be used. Let's examine just a few of the available switching devices.

The Gas Tube

Another switching device is the GAS TUBE, or THYRATRON. Gas tubes are triodes filled with an inert gas, such as hydrogen or mercury vapor. Unlike ordinary triodes, an external timing pulse must be applied to the grid of the gas tube before it will ionize and conduct. Gas tubes have low resistance during conduction. So long as the grid is negative, gas tubes will not conduct; but when a positive trigger is applied to the grid the gas in the tube ionizes and conducts freely. Once conduction begins, the tube acts as a diode and conducts until the network is discharged. At this time, the grid again can assume control of the tube. The gas tube is placed in series with the pulse-forming network and discharges the network when a trigger pulse is applied to the grid.

Gas tubes are very stable, and their switching action can be made to occur rapidly. Therefore, they can be used in radars having high PRFs. The chief disadvantage is the comparatively short life of the tubes under the high currents in the modulator. This disadvantage is not serious, however, and many Navy radars use gas-tube switches.

The Nonlinear Coil

Another switching device is the SATURABLE REACTOR or NONLINEAR COIL. You have studied saturable reactors in the Navy Training Course Fire Control Technician 3, NavPers 10173-A. The nonlinear coil is designed so that a very low current across the coil causes saturation. Saturation occurs when an increase in current no longer increases the number of magnetic lines of force (flux) through the coil. The voltage induced in a coil depends on the rate of change in the number of magnetic lines that link the coil. Thus, when the coil is saturated and there is no change in the number of magnetic lines, no voltage is induced in the coil even through the current is changing. When the coil is saturated it becomes a closed switch in the line, and when it is not saturated it acts as an open switch.

Consider figure 6-4A for a moment. This figure represents the number of lines of flux linking a nonlinear coil as the current changes. Assume that a current is impressed across the coil. As the current is building up at point 1, the flux is changing and a voltage is induced in the coil. This voltage serves as a counter-electromotive force (cemf) that opposes any current through the coil. Therefore, at point 1 the coil represents an extremely high impedance across the line and may be considered an open switch.

As the current across the coil continues to increase, point 2 is reached. At this point a further increase in current has no effect on the number of lines of flux linking the coil. This is the saturation point. At point 2 no cemf is induced in the coil because the number of lines of flux is constant. Thus, there is nothing to oppose the flow of current through the coil. This is the same as saying that the coil is a closed switch in the line. The action of a nonlinear coil can be compared to the mechanical action of the bottom of an oil can when you exert pressure on it. At first, the bottom resists movement, but when enough pressure is applied, it suddenly gives way, producing a clicking sound. The nonlinear coil first opposes current, then finally breaks down suddenly and passes a pulse of current.

Figure 6-4B shows how a nonlinear coil is represented in a schematic diagram. You can see that it is merely a coil symbol with a magnetization curve drawn through it.

PULSE TRANSFORMERS

The pulse obtained when the line is switched, is applied either directly to the r-f oscillator or, when the oscillator is separated from the modulator, through a PULSE TRANSFORMER. The pulse transformer is of special design and has a low turns ratio. Sometimes this turns ratio is only 1 : 2 or 1 : 4, because the pulse becomes distorted if the ratio is large. One advantage of having such a transformer in the circuit is clear if you consider that the size of the pulse-forming network can be reduced when you can charge the network to a voltage lower than the voltage normally required. As a consequence, the size of the coils and capacitors can be reduced, and the danger to personnel from high voltages in the modulator is lessened. Also, extremely high pulse voltages can be obtained from a comparatively small power supply. Another important advantage is that the pulse transformer can be used to match the impedance of the pulse-forming network with that of the transmission line.

OPERATION OF THE MODULATOR

Figure 6-5 shows a schematic diagram of a simple modulator, in which the pulse-forming network charges resonantly from a d-c power supply. In this figure, L1 is the charging choke. L1 is connected to the high voltage power supply through V3, the charging diode. The pulse-forming network, Z1, charges through V3 and L1. L1 is designed to be series resonant with the line. When the charging diode conducts the supply voltage to L1, the choke delivers a powerful positive inductive surge of nearly twice the supply voltage to the pulse-forming network. At this time the charge on the network blocks any

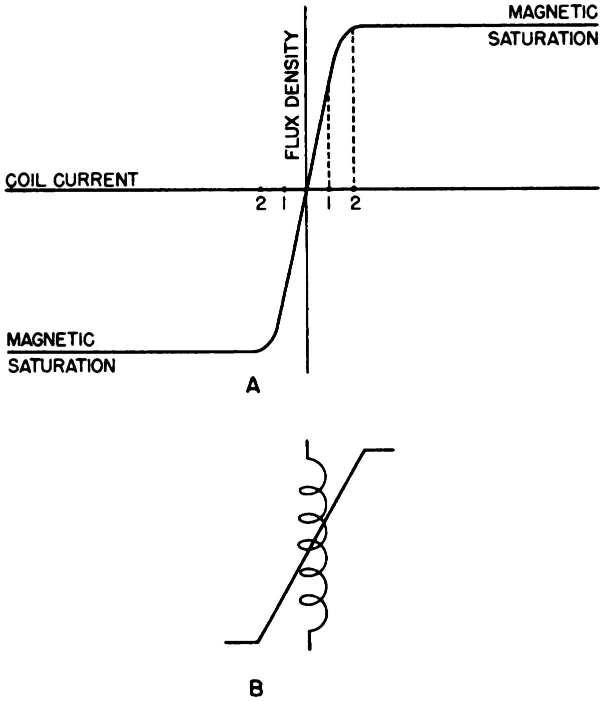

Figure 6-4.—Changes in flux with changing current in a nonlinear coil, with inset showing schematic diagram of a nonlinear coil. 55.73

further conduction of V3 because the cathode is more positive than the plate.

The switch tube, V2, does not conduct despite the high positive voltage on its plate because it is a thyratron and therefore must be ionized by a positive signal to overcome the negative bias on its grid before it will conduct. After the network has reached its maximum charge, diode clipper V1 delivers a positive trigger pulse to the grid of the thyratron switch. The high amplitude positive trigger ionizes the gas in the thyratron, thus allowing it to conduct. The thyratron switch now is a very low impedance, and the network can discharge. The discharge current flows from the capacitors through T_p and the thyratron to the other side of the capacitors. This sudden discharge current through T_p induces a large negative pulse in T_{s1} to drive the magnetron. The shape of this pulse is determined by the duration of the discharge, which in turn depends on the LC constants of the network.

Winding T_{s2} is the sync winding. A portion of the pulse is coupled off through T_{s2} to trigger the secondary timing circuits.

Diode V4 damps out any positive oscillations of the network that might follow the main discharge.

You may wonder why the high voltage supply is not shorted to ground through V2 after the network discharges. If L1 were not in the circuit, the thyratron would continue to conduct, thus shorting out the supply. However, when the network discharges, the choke blocks any sudden surge of current, so that more current from the power supply cannot pass until the thyratron has had time to deionize.

TROUBLESHOOTING THE MODULATOR

Radar troubles are found frequently in the modulator or in the associate high voltage supply. The currents and voltages in the modulator are so high that the elements have a short average life as compared with those in other units of the radar. For the same reason, the modulator is a dangerous unit to work on. A little fear is a healthy thing at this point, because fear promotes caution.

Radar Safety Devices

Although most radar equipment has safety devices, DON'T DEPEND ON THEM! It is safer for you to assume that you are working without any protection whatever. MOST safety devices work MOST of the time, but just one failure is all that is necessary for you or somebody else to lose his life.

Most radar safety devices operate on the same general principle—that is they cut off the high voltage supply when (1) currents are out of place or abnormally high, or (2) when somebody opens the radar equipment without shutting off the main power. As an example of the first group of these devices, the modulator, transmitter, and high voltage circuits have several overload relays, fuses, and thermorelays that protect both radar and technician when the currents are abnormally large or not where they belong. Remember that voltages still can be high without operating the relays or other devices, so don't trust the safety devices completely. Examples of the second group of devices are the interlocks that shut down the high voltage supply and short out the high voltage capacitors when the access doors to the radar cabinet are opened. During special repairs when it is necessary to run tests on an operating radar, the interlock switches must be shorted with

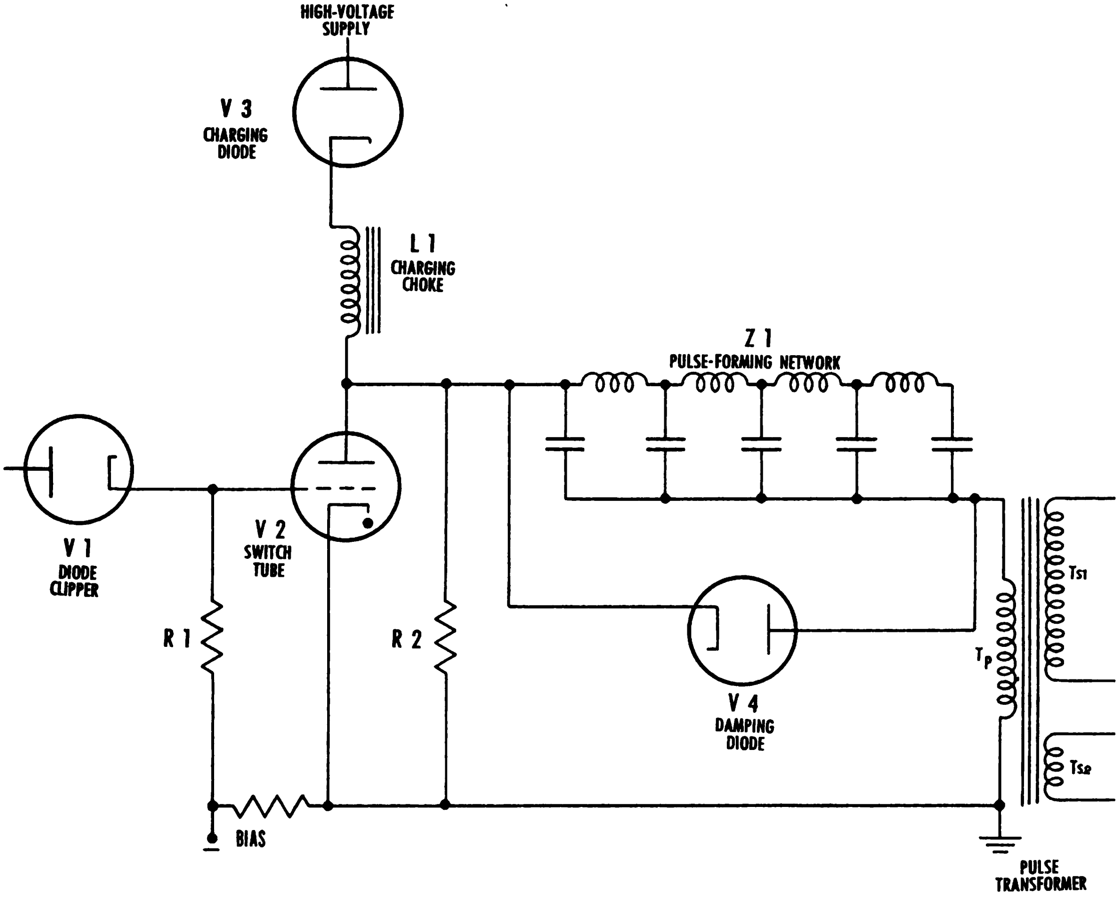

Figure 6-5.—Schematic diagram of a simple modulator.

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special cables; but this is a practice that must be avoided, if possible. In some equipments a battle-short switch is provided that can short the interlock switches. When it becomes necessary to short the interlocks, you must hang a sign on the radar to warn others that the interlocks have been shorted. Do not remove these signs until the interlock shorts have been removed. Most radars have pilot lamps that also indicate when an interlock is shorted, but this fact does not relieve you of your responsibility for placing a sign on the equipment.

A shorting bar and grounding cable is found in most electronic installations. If you do not find one, you can easily make one.

Isolating the Trouble

As in all troubleshooting procedures, you must first isolate the trouble to a particular unit by observing external symptoms. In this section you will learn a few of the symptoms of modulator failure and some general ways to isolate the trouble to a single component in the modulator. Remember that you are not to follow any of the troubleshooting procedures given in this book if they conflict with specific instruction in any radar instruction book. Such procedures are intended only to help you to become familiar with general troubleshooting techniques.

Either of the following symptoms may indicate modulator failure: (1) no radiation from the transmitter, as indicated by the absence of magnetron current, (2) visually by absence of transmitted pulse on indicator, or (3) poor radiation due to a misshapen pulse, as indicated by lowered or varying magnetron current. Also, if the secondary timing pulse is taken from the sync winding on the pulse transformer or elsewhere in the modulator output circuit, then there will be no timing pulses to the other units of the radar when the modulator is inoperative.

Common Modulator Troubles

Almost any element or component in the modulator is subject to possible failure. Therefore, you cannot say definitely that any one element is certain to fail before any other element. In general, however, fuses, relays, and tubes are most likely to fail; next in order are capacitors; and finally come resistors, transformers, and inductors. It is common sense (1) to use the signs of abnormal operation as clues in troubleshooting, (2) to test first those circuits that can be checked most easily, and (3) to test those circuits in which troubles are most likely to occur.

Troubles in the modulator usually can be isolated to one of three places—(1) power and relay circuits, (2) trigger circuits, and (3) high voltage circuits. Therefore, we shall discuss modulator troubles under these headings.

POWER AND RELAY CIRCUITS.—The power and relay circuits include those circuits through which primary power is supplied to the modulator. A large number of fuses and relays are found in these circuits. After isolating the trouble to the modulator, first check with a voltmeter to see whether primary power is present at the input. If the unit has primary power, next check all fuses and relays, because this takes little time and is a common cause of trouble. Most fuses have blowout lamps (indicators) that indicate when a fuse has blown; those without lamps you must check with an ohmmeter or by substitution. Fuses must be removed from the circuit when checking them with an ohmmeter. Always use a fuse puller in pulling or replacing fuses. Shut off the main power of the equipment when you are substituting fuses. Pull and replace only one fuse at a time to avoid replacing a fuse of the wrong rating in an unmarked socket. When the suspected fuses are replaced, energize the equipment to see whether the trouble has been corrected.

Sometimes relays burn out as a result of arcing, or they lock either in the open or in the closed position. Therefore, it is a good idea (1) to find the section in the OP that deals with the relays in question and (2) to check the operation of the relays against the OP data. This is done by standing clear of the equipment and energizing the unit to see whether the relays operate in the proper order. If a relay is inoperative or sluggish, you should shut down the main power and examine it. If the contacts are fouled, you can remedy the trouble by cleaning the contacts with a burnishing tool. Look for poor connections or signs of arcing. If the relay still fails to operate properly after the equipment is energized, the coil probably has burned out or is shorted; therefore, you must replace the relay. Do this only with the main power off.

TRIGGER CIRCUITS.—The trigger circuits include all the amplifying, shaping, and limiting circuits through which the main trigger passes before being applied to the switching device. In some radars a large number of trigger elements are located in the modulator; in others, most of the trigger elements are in the synchronizer with only one or two in the modulator. In either case, the OP gives test points to check for the presence of the trigger. You can check tubes in the trigger circuit by substitution from the spares that have been tested previously in the equipment.

The tube-base diagrams in the OP give test voltages for each socket connection in the trigger circuit. You must check these voltages with a calibrated synchroscope or a high-input-resistance voltmeter as indicated in the OP.

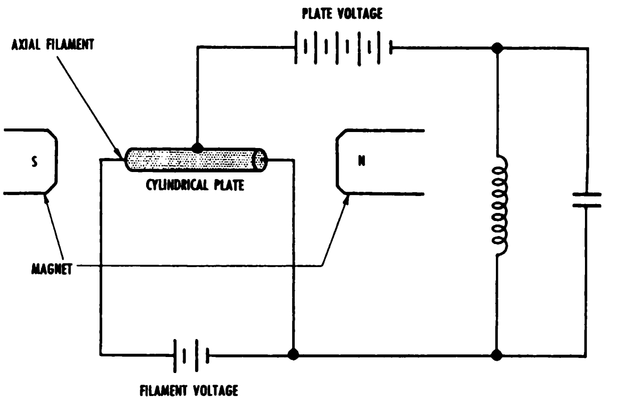
HIGH VOLTAGE CIRCUITS.—High voltage circuits include high voltage rectifiers, input diodes, the charging device, the pulse-forming network, and the switching device, plus any associated elements. Here is where you must exercise extreme caution. Be sure that the equipment main power is off and that all elements with which you might possibly come in contact are grounded before touching the interior of the equipment to make a test. Observe all the safety precautions in the OP.

Voltage measurements must be made with a high-input-resistance voltmeter. Make all measurements across a resistance voltage divider to ground so that no more than 1000 volts is across the voltmeter at any time. IF POSSIBLE, AVOID MAKING VOLTAGE MEASUREMENTS ON HIGH VOLTAGE CIRCUITS. When you make these measurements, shut the equipment main power off and connect the test leads with alligator clips or lugs. Then turn the main power on and read the meter. Stand clear of the meter, the test lead, and the equipment when doing this. Repeat this procedure for each measurement that is necessary. Your radar instruction book

(OP) gives the correct voltages at all tube socket connections and indicates test points for checking all major circuit components.

The pulse-forming network usually is encased in a separate container or unit. If measurements at the test points prove that it is faulty, you should replace the entire unit, because the design is so critical that you are not likely to repair it accurately.

If the switching device proves to be defective, you must replace it from the spare parts stock. Then you should check to see if it is operating properly.



55.75

Figure 6-6.—Circuit of a basic magnetron.

BASIC MAGNETRON

The first thing for you to remember in understanding the magnetron is that any electric current is a stream of electrons. A magnetic field exerts a force on electrons in motion. The deflection of an electron beam in an electromagnetic cathode-ray tube is an example of this fact. In such a tube the spot is positioned simply by changing the current through the deflecting coils. This changes the magnetic field in the tube and moves the stream of electrons on the face of the indicator. If this principle is clear to you, the rest is easy, because in a magnetron a stream of electrons is acted upon by a magnetic field.

Let's strip the magnetron of its trimmings and start out with a basic circuit. Figure 6-6 is a diagram of a basic magnetron circuit. Examine the magnetron carefully. The plate is represented as a cylindrical piece of metal, and the cathode extends through the axis of the plate cylinder. Notice the permanent magnet in the figure. The magnetic lines of force from pole to pole pass through the plate cylinder parallel to the cathode. The electric field, with which you are already familiar, extends from the cathode to the plate. If you think of a wagon wheel with the axle representing the cathode, then the spokes extending from the axle to the rim of the wheel represent the electric field. The rim to which these spokes are attached is the plate.

Effects of the Two Fields

You can see that the magnetic field and the electric field are at right angles to each other. If only the electric field were present, an electron emitted from the cathode would be pulled to the plate in a straight line. You are familiar with this effect, because electrons travel in this manner in a conventional diode. Now assume that you move the magnet into the circuit. An electron emitted by the cathode is acted upon by two forces—the electric field and the magnetic field. You know how the electron behaves in the electric field. The magnetic field exerts a pull on an electron AT A RIGHT ANGLE TO THE MAGNETIC FIELD and AT A RIGHT ANGLE TO THE DIRECTION OF MOTION OF THE ELECTRON. This pull increases directly as the speed of the electron increases.

The left-hand rule will help you to understand the force exerted on an electron by the magnetic field. With your left hand held in the vertical plane, extend your thumb to the right and your index finger into the page in a pointing position. Now extend your second finger at right angles to both your thumb and your index finger. With your hand held in this position, if your second finger points in the direction of the electric field and your index finger in the direction of the magnetic field, your thumb indicates the direction of the force exerted on an electron by the magnetic field.

Now consider the forces that affect an electron when both fields act upon it. The electric field tends to pull the electron directly to the plate at an increasing speed. The magnetic field, however, tries to pull the electron at right angles away from its direction of travel. As the pull exerted by the magnetic field is a function of electron speed, the faster the electron is pulled by the electric field toward the plate, the stronger is the pull of the magnetic field. The combined influence of the magnetic and the electric field thus tends to move the electron into a circular path away from the plate.

What Happens to the Electron?

Figure 6-7 shows some possible electron paths in a cylinder having an axial magnetic field and a radial electric field. Paths 1 through 3, respectively, are for the case of a very strong magnetic field, a weaker magnetic field of just sufficient strength to cause the electron to strike the anode of grazing incidence and a very weak magnetic field. In each case the magnetic field exerts a force on the electron at right angles to the direction of its velocity.

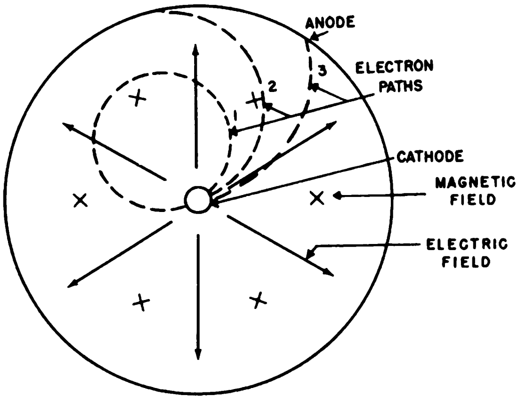


Figure 6-7.—Electron path in perpendicular electric and magnetic fields. 55.76

In the case of the split anode magnetron (fig. 6-8), the electron, which never actually stops moving, follows a spiral path. This spiral path is essential to the operation of the magnetron because it is the source of the r-f oscillations. Since the magnetic field affects this path, you know that its strength is important. If the magnetic field is too strong, the electron never quite reaches the plate and circles back to the cathode; then there is no output from the tube.

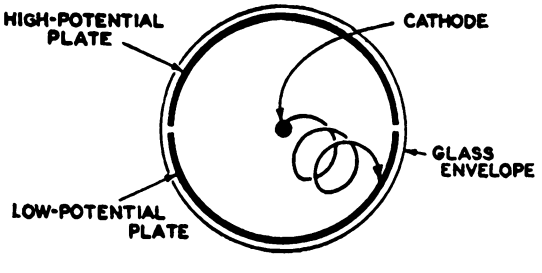


Figure 6-8.—Spiral path of an electron in a split anode magnetron. 55.77

On the other hand, if the magnetic field is too weak, the electron travels to the plate in a curved path and does not go through the oscillations that are necessary for the proper operation of the magnetron.

Now that you have a mental picture of the way an electron behaves in a basic magnetron, you probably would like to know how the magnetron in your radar operates. The operation is similar to that just described; about the only new factors you need to consider are those created by other magnetron elements that have not been mentioned yet. Therefore, the next step is to discuss the complete magnetron.

Figure 6-9 shows a schematic diagram of a magnetron oscillator. Notice in the diagram that the plate, or outer shell, is grounded and that the high voltage pulse is applied directly to the cathode of the magnetron. More will be said about this in the next few pages.

Anode Block

The plate, or anode, of a magnetron is the metal outer shell. There are tuned circuits which are cavities in the anode. Three common types of anode block are shown in figure 6-10.

The first type of anode block in figure 6-10 has cylindrical cavities that are carefully constructed to resonate at the frequency of the magnetron. This type is called a HOLE-AND SLOT anode.

The second type has regular trapezoidal cavities, also designed to resonate at the frequency of the magnetron. These first two anode blocks operate in such a way that alternate cavities must be connected. This connection is called STRAPPING. STRAPS are circular metal bands that are placed across the top of the block at the entrance slots to the cavities. These bands electrically connect the alternate segments during the operation of the magnetron and ensure that each segment is opposite in polarity to its neighboring segment on each side.

The third type shown in figure 6-10 is called a RISING-SUN block because of its appearance. The alternate large and small trapezoidal cavities in this block result in a stable oscillating frequency between the resonant frequencies of the large and small cavities.

The Cathode

Most magnetrons operate with the anode block grounded. The high power d-c pulse therefore is applied to the cathode, which has the same effect as a large positive potential applied to the plate. As the cathode must operate at high

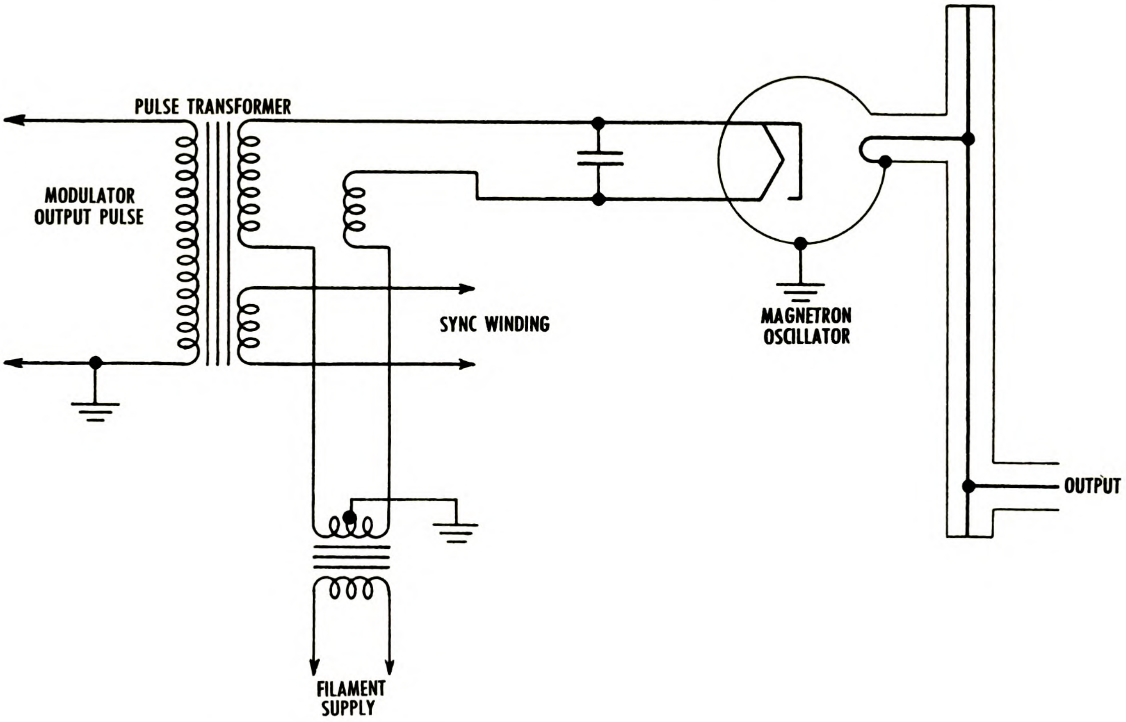


Figure 6-9.—Schematic diagram of a typical magnetron r-f oscillator circuit. 55.78

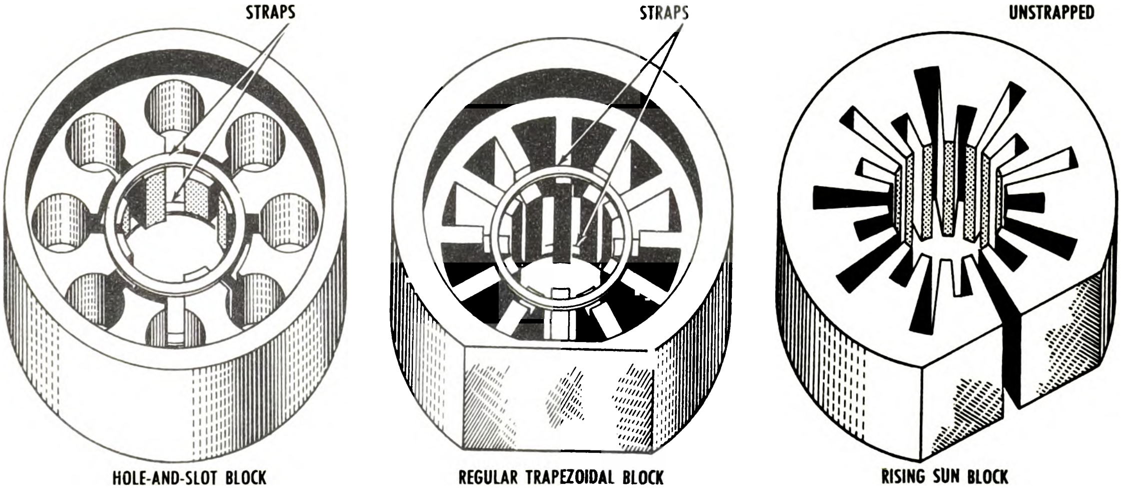


Figure 6-10.—Common types of anode block. 55.79

power, it must be fairly large and must be able to withstand the high operating temperatures. The cathode also must have good emission characteristics, particularly under back-bombardment, because much of the output power is derived from the large number of electrons emitted when high velocity electrons return to strike the cathode.

The magnetron cathode is shown in figure 6-11. The cathode is indirectly heated and is constructed of a high emission material. Although it is large compared with most ordinary

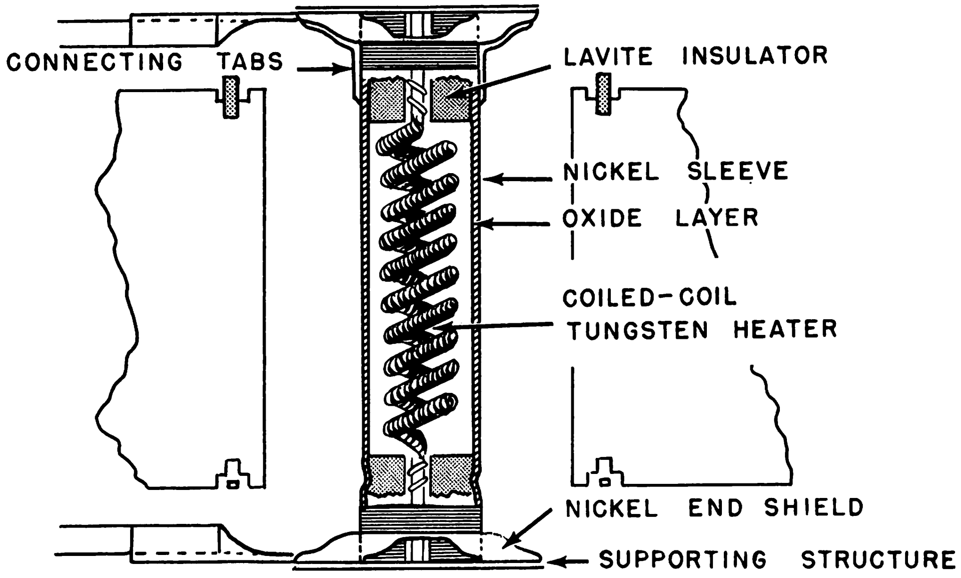


Figure 6-11.—Cutaway view of magnetron cathode. 55.80

cathodes, it does not fill the entire interior of the anode block, and end shields are made to cover the open space between the cathode and anode. These shields are maintained at the potential of the cathode. The open space between the anode and cathode is called the INTERACTION SPACE, because it is in this space that force upon the electrons. The end shields are used to prevent loss of electrons from this space.

Operation

Electrons emitted by the cathode of the magnetron are acted upon by the electric and magnetic fields, as described earlier. The spiraling electrons in the interaction space set up high frequency oscillations, which travel as waves of r-f energy to the end slots of the tuned cavities. In terms of the currents in the anode block, the tuned cavities may be thought of as a series of tank circuits (fig. 6-12A). The traveling waves set up by the moving electrons cause alternating currents across the walls of each end slot, thus producing the effect of capacitor plates. On entering the large cavity resonators, the traveling waves are acted upon by the magnetic field, as in an inductor. Therefore, the walls of the end slots in the magnetron act as capacitors, and the cylindrical cavities act as inductors. The overall equivalent circuit for the group of cavities is shown in figure 6-12B. This circuit is derived from figure 6-12A, and is the equivalent tank circuit for the magnetron.

Output Circuit

The oscillations set up in the cavities are coupled out by means of either (1) a loop or probe extending into one of the cavities (fig. 6-13A), or (2) a slot extending into a cavity (fig. 6-13B). As the coupling is critical, the designer must be extremely careful in locating the loop or slot. This is one of the reasons why you must handle magnetrons, and especially the leads, with great care. Damage to these leads may result in r-f unbalance and losses in the system and may cause the magnetron to stray dangerously off-frequency.

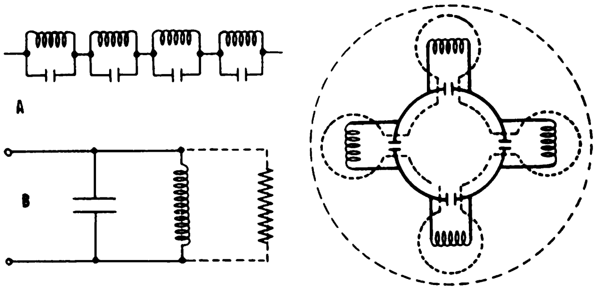


Figure 6-12.—Equivalent circuis for a 4-cavity magnetron. 55.81

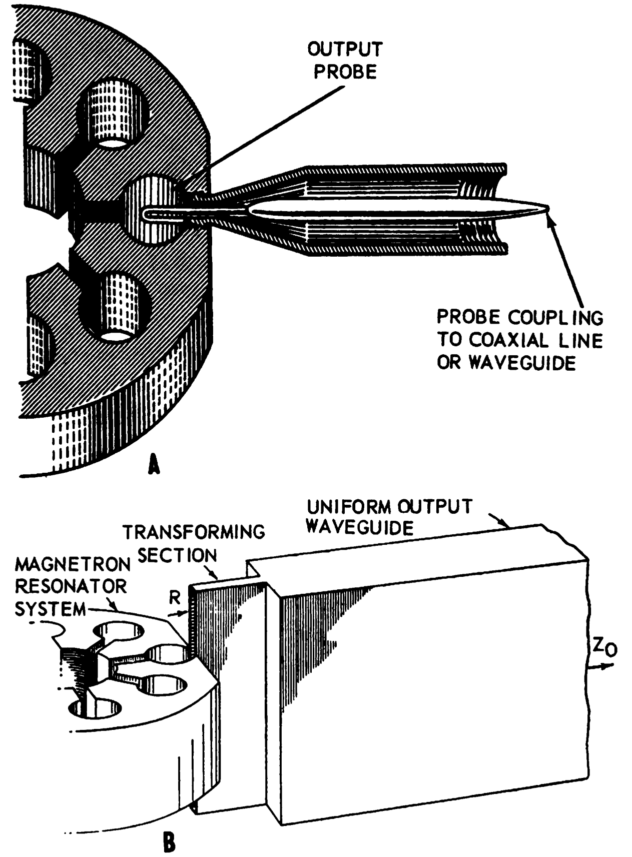

OUTPUT PROBE
PROBE COUPLING TO COAXIAL LINE OR WAVEGUIDE
A
UNIFORM OUTPUT WAVEGUIDE
TRANSFORMING SECTION
MAGNETRON RESONATOR SYSTEM
R
Z0
B

Figure 6-13.—Methods of coupling the magnetron output to a waveguide or coaxial line. 55.82

Magnets

Most magnetrons use permanent magnets to set up the magnetic field. A few magnetrons, which you are not likely to see, use electromagnets. When permanent type magnets are built into the magnetron itself, the tube is called a PACKAGED magnetron; or the magnets may be separate units designed so that the magnetron fits between the pole pieces.

Most magnetrons require a uniform magnetic field of about 3000 gausses in strength. As this is a rather high value of field intensity, the magnets used with some magnetrons are large. Metal tools should not be brought near the magnet. A light blow from a screwdriver attracted to a magnet can cause the loss of 30 gausses or more in field strength. Because it is important to have the exact strength of magnetic field for which the magnetron was designed, you must be extremely careful in handling magnets. When they are not being used in a radar, the metal blocks, or keepers, provided with the magnets should be kept between the pole pieces.

The intensity of the magnetic field may be varied in some radars by changing the position of the poles with respect to the magnetron. In this way the magnetron can be tuned over a narrow range of frequency.

Tuning and Stabilization

Magnetrons are inclined to stray from their proper frequency even under the most ideal conditions. Normally, this straying does not make much difference because the automatic frequency control (AFC) in the receiver adjusts the frequency of the local oscillator to compensate for variations. Sometimes, however, as when trying to jam an enemy frequency or to avoid enemy jamming of your own frequency, you must be able to hold the transmitter on a given frequency or to vary the frequency slightly from time to time.

TUNABLE magnetrons are used in more modern equipments. These magnetrons have devices that permit the frequency to be tuned over a narrow range.

METHODS OF TUNING.—A magnetron is difficult to tune because the tuned circuits, or cavities, are located in the vacuum inside the magnetron. These cavities are extremely hard to reach from the outside. However, mechanical and electronic methods of tuning have proved successful over small ranges in frequency. Tuning ranges up to 10 percent of the magnetron frequency have been achieved with each of these methods.

Mechanical Tuning.—Mechanical tuning can be defined as any method of tuning that does not involve the injection of additional electrons into the r-f field. It generally takes the form of changing the capacitance or the inductance of one or more tuned cavities in the magnetron anode block. However, mechanical tuning also can be done by adding an external tuned cavity or tuning stub in the output line.

VANE tuning is an example of one of these mechanical tuning methods. Small vanes are inserted into the end slots leading into the resonant cavities of the magnetron (fig. 6-14). These vanes, or plates, are inserted into or withdrawn from the end slots by means of a set of gears connected to a shaft extending into the anode block and attached to the plates. Because the sides of the end slots act as the plates

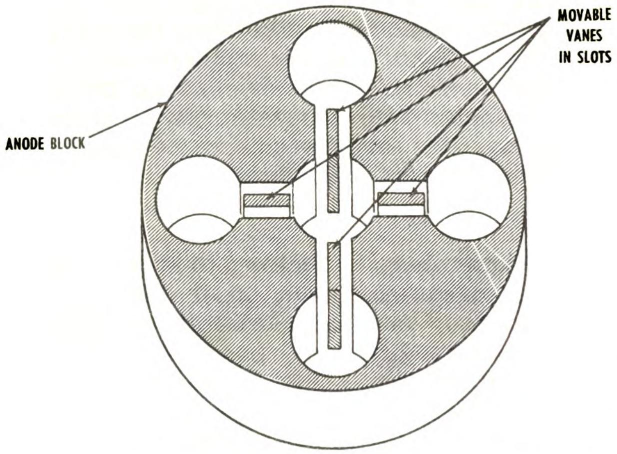


Figure 6-14.—Cutaway view of a vane-tuned magnetron. 55.83

of a capacitor, the insertion of the new conducting surfaces between the slots changes their capacity.

PLUG tuning is achieved by the insertion of plugs into the resonant cavities, as shown in figure 6-15. This changes the inductive tuning, and therefore the resonant frequency, of the cavities. A gear arrangement similar to that just described transmits the external motion within the magnetron.

In some tunable magnetrons, circular U-shaped metal bands are used for tuning. These bands usually are placed in special slots around the top of the anode block within the magnetron. They may be inserted into or withdrawn from the slots by a gear arrangement similar to that used with the plug or vane method.

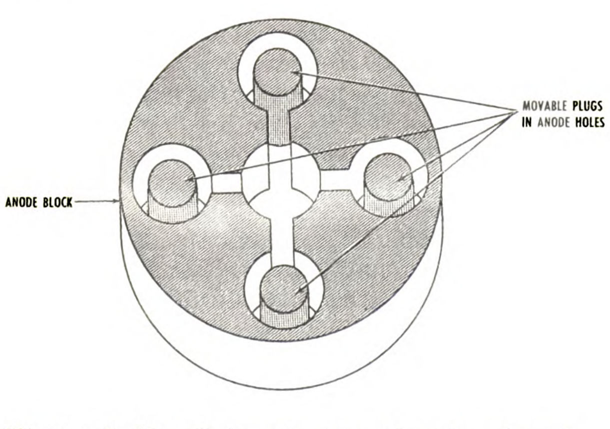


Figure 6-15.—Cutaway view of a plug-tuned magnetron. 55.84

You can also vary the magnetron frequency over a small range by means of a tuning stub. You must carefully match and position this tuning stub in the output line. Take care to avoid r-f losses at the joints. By changing the effective length of the tuning stub, you can make small changes in the output frequency.

Electronic Tuning.—Electronic tuning includes all methods of tuning that involve the addition of electrons to the r-f electron beam set up by the magnetron. This type of tuning is accomplished by adding an extra metal tube in the magnetron output. This tube may have a grid, or it may be a diode. Most turning tubes are attached directly to the side of the magnetron.

Tuning is done by passing the magnetron output through the beam of electrons in the tuning tube. As the intensity of the beam is changed, the magnetron output is frequency-modulated.

STABILIZATION.—Stabilization is considered with tuning because the two processes are related. Stabilization of the magnetron frequency is necessary in special cases when the frequency changes of the magnetron need to be limited to a very small range or when the Q of the magnetron tanks is quite low.

Stabilization is essentially an energy-storage process. The magnetron, being a low-Q oscillator, is a poor device for storing r-f energy. The stabilizer, on the other hand, presents a high Q at the frequency of the magnetron and is therefore an efficient storage chamber.

Most stabilizers take the form of tuned cavities connected in the output plumbing a few wavelengths away from the magnetron. As the coupling between the low-Q magnetron and the high-Q stabilizing cavity is critical at the radar frequency, some magnetrons are designed with a special built-in r-f lead for the stabilizing cavity. If the stabilizer is added after the magnetron is installed, the takeoff section from the r-f plumbing has a knurled knob or nut to adjust the coupling.

The stabilizing cavity itself is a tuned r-f tank designed to present a low impedance to all frequencies except the magnetron fundamental frequency. Thus, when the magnetron output is coupled into the stabilizer, the stabilizer resonates at the fundamental frequency and the many sideband frequencies tend to be damped out.

Energy from the resonating stabilizing cavity is used to reinforce the fundamental magnetron output. The energy may be considered, therefore, as regenerative feedback from an equivalent circuit like that shown in figure 6-16. As the stabilizer effectively reinforces the fundamental frequency and damps out the undesirable sideband frequencies, you can think of the stabilizer as a simple form of automatic frequency control for the magnetron.

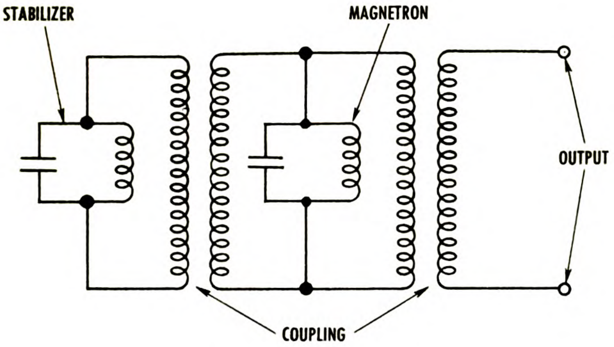


Figure 6-16.—Equivalent circuit of magnetron and stabilizer. 55.85

Checking for Proper Magnetron Operation

All fixed-frequency magnetrons have output circuits tuned to a specified frequency. This factor is helpful in providing a check on the operation of the magnetron. If the magnetron operates at a different frequency, then it is not operating at maximum efficiency. The result may be a drop in plate current. Therefore, a frequency shift may show up as a drop in plate current that you can see on the plate-current meter.

WATCH THE PLATE-CURRENT METER.—The simplest and surest check for the proper operation of a fixed-frequency magnetron is to watch the plate-current meter. Your radar OP gives an approximation, in milliamperes, of the best operating reading. In addition, you should take daily readings and enter them in the radar log. The average of these daily readings is a good figure to compare with the operating readings to see whether the magnetron is operating properly. You should not take readings immediately after turning on the radar, however, because the magnetron requires a few minutes to get warm and to become stable. Also, readings are unstable for a short time after a new magnetron is installed because of the seasoning time required to break in the magnetron.

ECHO BOX.—If there is any mismatch in the output line or waveguide, incorrect frequencies may give maximum readings on the plate-current meter, and the efficiency and range of the set are lowered. Therefore, you need a device to read the magnetron output frequency directly. This device is the tunable ECHO BOX.

The echo box (fig. 6-17) is a tunable resonant cavity connected to a crystal rectifier and a milliammeter. A portion of the transmitter pulse is coupled out of the waveguide and is fed into the cavity. The cavity then is tuned by turning a calibrated dial until a maximum reading is obtained from the meter. At this point, the cavity is tuned to resonance at the radar frequency, and this frequency can be read either directly from the dial or from a calibration chart giving dial readings as a function of frequency.

One function of this echo box is in making a SPECTRUM ANALYSIS of the radar pulse. A radar pulse consists not of a single frequency but of a band of frequencies centered in one fairly small range. A pulse spectrum is shown in figure 6-18. The spectrum is obtained by tuning the echo box over the entire range of frequencies in the radar pulse and plotting the meter readings at intervals on a graph. It can be used in several ways. When a radar is first installed, a spectrum reading is usually run to make sure

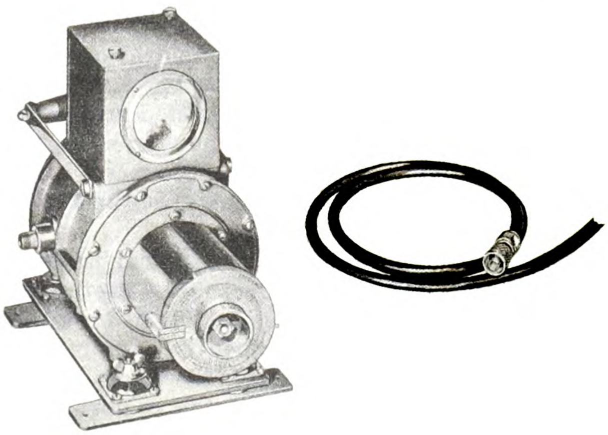


Figure 6-17.—An echo box and a waveguide connector. 55.86

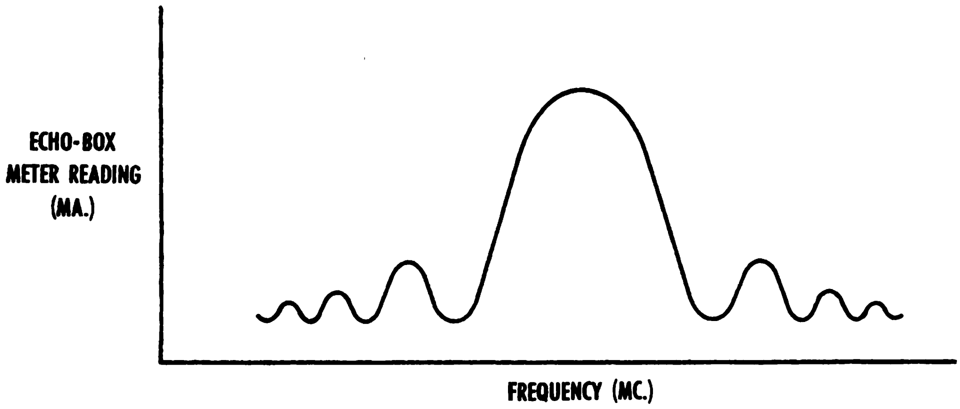


Figure 6-18.—Spectrum of a radar pulse.

55.87

that too much power is not dissipated in the sideband frequences of the pulse. A poor spectrum, with large sidebands, indicates a defective magnetron, a mismatch in the output line, or a misshapen modulator pulse. You will learn more about spectrum analysis in a later training course in this series.

Other major functions of the echo box include the testing of receiver sensitivity and the tuning of the receiver. Some fire control radars have a nontunable echo box preset at a particular frequency for tuning the receiver. However, this function is covered in the chapter later, and need not concern you now.

ARCING.—Arcing of the magnetron is a warning sign that you must watch for. Arcing shows as bright flashes of light across the magnetron input leads. You can hear it as a crackling or sputtering sound. A small amount of arcing is to be expected, especially when the radar is first turned on or when a new magnetron has just been installed. However, you must learn from experience when arcing is dangerous and when it is temporary and harmless.

Arcing can be caused by several troubles. One common cause of arcing is allowing the input voltage to become too high. When due to this cause, arcing can be stopped by lowering the voltage until the reading on the plate-current meter is normal. If the arcing is not stopped soon after beginning, the cathode may be burned out.

Another cause of arcing is a block of mismatch in the output line that causes the r-f energy to be reflected. A mismatch sets up standing waves in the line. When the coupling is adjusted properly, the standing waves are removed and the arcing ceases. In radars having a crystal-protection relay in the waveguide, arcing sometimes means that the relay is locked shut, thus obstructing the waveguide. When the relay is opened or replaced, the arcing stops.

An aging magnetron can cause both arcing and low magnetron output, as indicated on the plate-current meter. If the cathode or one of the straps is nearly burned out, or if one of the straps has shorted, arcing usually results. Therefore, if arcing occurs together with a low plate-current reading, and if the arcing cannot be stopped by lowering the input voltage, the magnetron should be replaced.

If either of the magnetron input leads is bent so that it shorts the filament against the surrounding input pipes, arcing is almost certain to occur. This cause of arcing is usually easy to detect because the plate current is absent or unusually erratic.

TROUBLESHOOTING THE TRANSMITTER

Now that you understand the modulator and r-f oscillator, you should be able to diagnose and correct most of the difficulties that arise in the transmitter circuits. Always remember that radar troubleshooting is not a process of doing things in one-two-three fashion, no matter what the trouble is. When trouble arises, you must know your equipment and know how it works so well that you can narrow the trouble quickly to one possible cause or to a few possible causes. Then you can proceed to check each one of these causes in its logical order until the difficulty is located.

Possible Causes of Trouble

For example, assume that the magnetron plate-current readings have been decreasing over the last three daily readings. You know from these readings that the trouble must lie somewhere in the transmitter circuit. Because you know the function of each unit, you know that the trouble can be the result of one of three causes: (1) the magnetron is defective, (2) the input pulse to the magnetron is misshapen, or (3) standing waves have been set up because of a mismatch in the waveguide or output line.

You rule out the last of these three causes as unlikely because the drop in readings has been steady. A mismatch gives a drop or rise when it first occurs.

Thus, you have narrowed the trouble down to two possible causes. As the input pulse to the magnetron is of high power, it is difficult to measure whether it is of the proper voltage. However, you can reason that if the output pulse from the modulator is faulty, the trouble is most likely the result of either (1) a weak tube in the modulator or power supply, or (2) a defective element in the pulse line. You can see that replacing the magnetron will take more time than running a test on the modulator; so the logical step to take first is to test the modulator. When actually performing any of the operations described, however, let the OP be your guide.

Replacing the Magnetron

The best practicable way to check for a defective magnetron is to replace it. Shut down the equipment and ground the storage capacitors as previously described. Following the instructions given in the radar OP, replace the magnetron. Handle the old magnetron with care, because it may still be good. Pack it carefully in a box and store it in a dry, cool place. In replacing the new magnetron, make sure the r-f coupling is thoroughly clean and secure. Check the spaces on both sides of the magnetron between the anode block and each pole piece. See that these spaces are equal and that the magnetron is centered between the poles.

Remember to remove your watch when working near the magnet because the field is very strong and will magnetize the watch quickly. Do not bring metal tools near the magnet, for a light blow from a metal tool can cause a serious loss in the field strength of the magnet.

In handling the magnetron itself, take care to protect the input and r-f leads. Some magnetrons have a tolerance of less that 0.04 inch between the input leads and the metal lead-in pipes. If the leads are bent only slightly, they are likely to short the filament and ruin the magnetron. All contacts must fit smoothly without forcing. Always keep in mind that a magnetron is expensive and that it can be damaged easily.

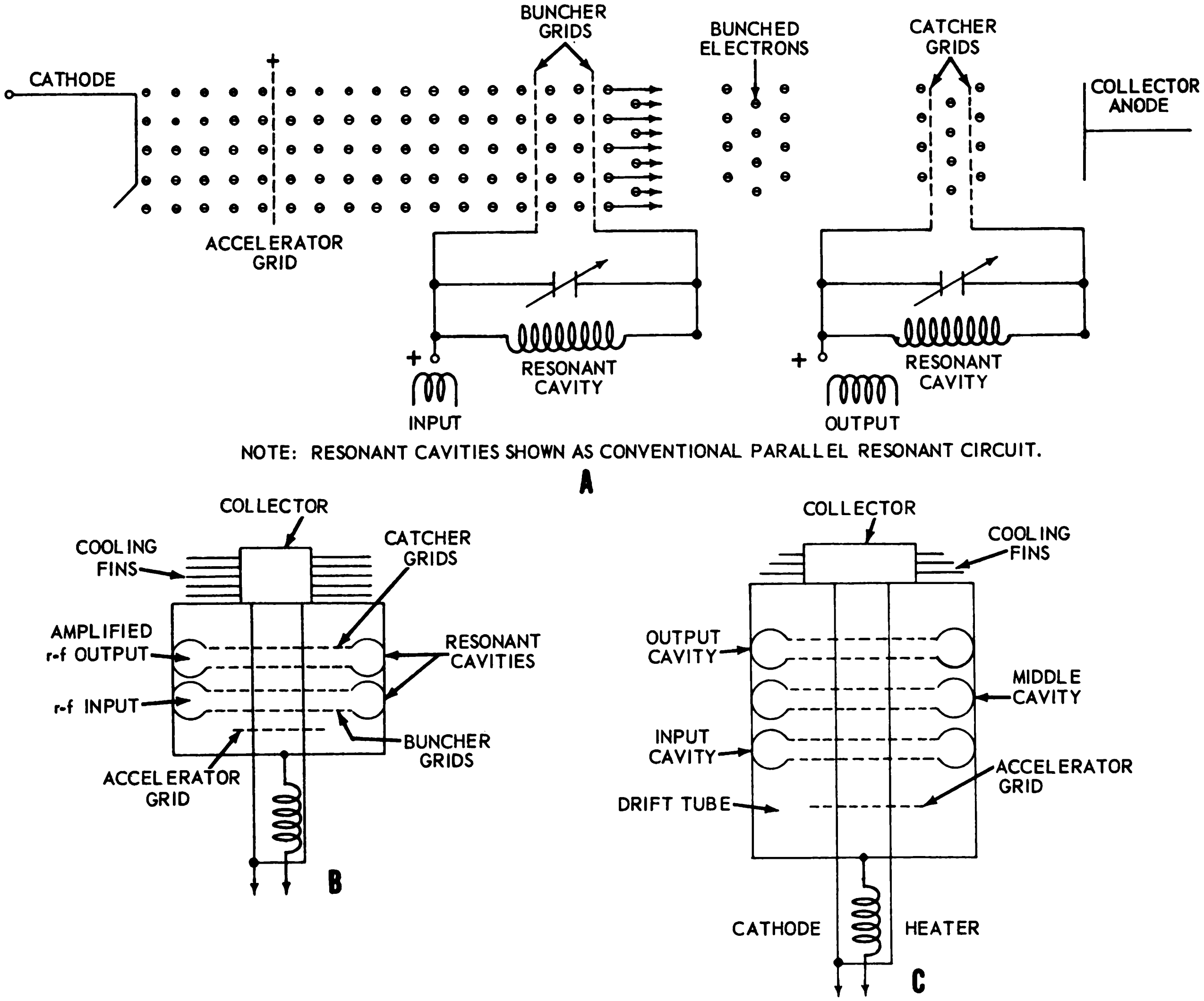
Seasoning the New Magnetron

After the new magnetron has been installed, doublecheck to make sure that all leads are tight with proper tolerances and that the magnetron is centered correctly. Turn on the radar main-power switch and apply heater voltage to the magnetron. Allow the tube to warm up for about 5 minutes and then apply the high voltage gradually. Keep increasing the input voltage slowly until the normal operating valve is reached or until excessive arcing occurs. If arcing occurs, reduce the voltage slightly until the arcing stops and allow the magnetron to operate at the reduced voltage for about 5 minutes. Then build up the voltage until it reaches normal operating value or until arcing occurs again. This process should be repeated until the new magnetron is operating steadily at normal operating power. For the first 10 or 15 minutes you can expect slight arcing and variations in the output current because of gas that has accumulated in the magnetron while it was sitting idle on the supply shelves.

If the magnetron overload relay snaps out when the high voltage is applied, reset the relay and repeat the process at least five times before you decide that the replaced magnetron is defective.

KLYSTRONS

Klystrons are used in some radar transmitters as a source of transmitted r-f power and for power amplification. These klystrons usually have two or more resonant cavities. Another type employing one cavity, called a reflex klystron, is used as a local oscillator in the receiver. Figure 6-19A is a schematic view of a 2-cavity klystron used as an amplifier. Part B shows a cross section of the same klystron. The tube contains a cathode, collector anode, and three grid assemblies. Two of the sets of



A. Electrical representation of 2-cavity klystron
B. 2-cavity klystron
C. 3-cavity klystron

Figure 6-19.—The klystron.

55.88

grids are surrounded by resonant cavities, and the third single grid is used to accelerate the electrons. A high velocity electron beam is emitted from the heated cathode. The electrons pass through the accelerator grid, where they pick up more speed. An r-f input is fed into the buncher cavity to excite the cavity into resonance and produce an oscillating voltage. The oscillating voltage is fed from the cavity to the buncher grids where it speeds up some electrons in the beam and slows down others. This acceleration and deceleration process is called velocity modulation. In the drift space past the buncher grids the faster electrons catch up with the slower ones and form bunches. The bunching effect is called density modulation. The electron bunches pass through the catcher grid, where they excite the tuned cavity into oscillation at its resonance frequency, and an r-f voltage is generated. This r-f energy is greatly amplified because some of the energy in the electron beam, which is direct current is converted into r-f energy. The r-f voltage is coupled out of the cavity by a coaxial loop or a waveguide opening (window). The greater part of the d-c electron beam energy reaches the collector anode and is dissipated as heat. The purpose of the cooling fins surrounding the anode is to absorb and dispel this heat.

Three-cavity Klystron

Amplification and efficiency are increased if we add a third cavity to our 2-cavity klystron. Figure 6-19C shows a cross section of a 3-cavity klystron. The middle cavity acts as an intermediate stage of amplification. The third cavity also acts as a buffer or isolation stage between the first two cavities and the load. This helps to prevent frequency pulling. The term "frequency pulling" is applied to describe a change in output frequency caused by a change in load impedance.

Klystrons with more than 3 cavities, called multicavity tubes, have been developed for fire control radar applications. Their specific operating principles are discussed in the applicable OP; however, their basic operation is essentially like that of the 2-cavity tube discussed here.

ANTENNA SYSTEM

As you know, the purpose of the antenna system is to feed energy from the transmitter to the antenna, and to radiate the r-f energy into space. The reflected energy is then fed to the receiver. The major components that make up the antenna system are the antenna itself, the waveguide plumbing or connecting coaxial cables, and the duplexer. In chapter 5 antennas were discussed in some detail; therefore we will not discuss them here. However, operating principles of the other components that comprise the system deserve a brief description.

RADAR R-F LINES

The high powered r-f output pulse from the r-f oscillator is coupled into the r-f line. The r-f line, in turn, leads to the radar antenna. You may think that delivering the r-f energy to the antenna is a simple matter, but it is not. At the extremely high frequencies used in radar, ordinary transmission lines are inefficient and wasteful. You already have learned that it is very important for the radar to use every watt of energy possible in order to get maximum range. Thus the efficiency of the r-f line is vital to the effective use of the radar, because every bit of energy lost in the transmission line means that the enemy can come closer before being detected.

The earliest radars used open 2-wire transmission lines. These lines worked fairly well at the low r-f frequencies used at that time. As radar frequencies were increased, however, these lines became inefficient. Coaxial lines were used in the next stage of radar development, but they also were inefficient at frequencies in the s-h-f band. Continued research led to the development of the waveguide, which now is used as a transmission line in most radars.

Let's look at a few transmission lines.

Open Two-Wire Lines

An open 2-wire line is the simplest type of transmission line. It consists of two lines running side by side with insulated spaces, or supports, at intervals to keep the lines separated. Figure 6-20 shows an open 2-wire line.

Because open 2-wire lines are not shielded, they lose energy by radiating waves along the line. The radiation losses increase with frequency, thus making the lines impracticable for use at frequencies above 300 megacycles. Open lines also are subject to stray capacitive and inductive couplings, which can cause interference with nearby electronic equipment.

Coaxial Lines

Another transmission line is the coaxial, or CONCENTRIC, line. A coaxial line is shown in figure 6-21. It consists of a center conductor surrounded by a tubular outer conductor. Spacers are placed at intervals inside the line to keep the two conductors apart. A dielectric, such as dry air, a dry inert gas, or a solid, inside the line insulates the two lines from each other. Gas is not used frequently, because keeping the lines gastight under battle conditions or in rough seas is difficult.

Most coaxial lines operate with the outer conductor at ground, because the outside of the line

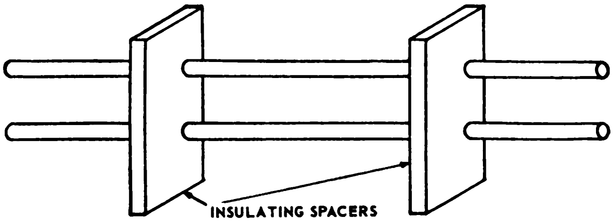


Figure 6-20.—Open 2-wire transmission line.

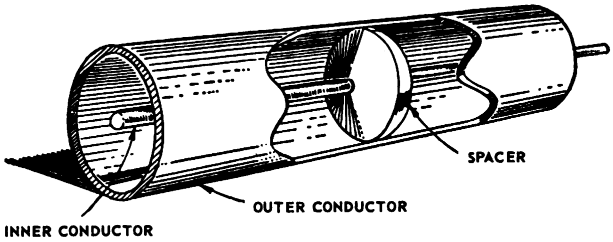


Figure 6-21.—Coaxial, or concentric, transmission line. 13.46.5

is thus shielded to prevent losses from inside the line or stray capacitive or inductive couplings. Despite this shielding, however, skin and corona losses make the use of long coaxial lines impractical at frequencies above 1000 megacycles.

Transmission Line Characteristics

WAVES ON A LINE.—If you take a very long hemp line and shake one end, the wave you produce travels away from you toward the other end of the line. Note that the crest of the wave keeps moving down the line. This is a TRAVELING WAVE or TRANSMISSION WAVE.

If you now tie one end of a shorter piece of line to a rail and shake the line at the proper frequency, you set up waves that appear to stand still on the line—that is, the crests and nodes of the wave appear to be stationary. This kind of wave is called a STANDING WAVE. You must shake the line at the proper frequency to set up standing waves, because they are produced only when the reflected waves from the rail are in phase with the waves you produce when you shake the line. In other words, the standing waves are produced when the line is resonant. Thus, an r-f transmission line with the standing waves is said to be resonant. A transmission line with only transmission waves is said to be NONRESONANT. In the next few pages you will learn more about these waves and how they are produced in a transmission line.

CHARACTERISTIC IMPEDANCE.—All transmission lines offer a certain amount of resistance to the flow of current. In addition, because of the regular rise and collapse of magnetic lines around a conductor, even a solid copper wire acts like a coil and has some inductive reactance to the flow of current in the wire. The capacity between two conductors has some capacitive reactance. The capacitive reactance decreases as the lines are moved farther apart. Increasing the size of the conductors decreases the inductive reactance. There is also leakage current through the dielectric.

The impedance to the flow of current offered by these four factors—capacitive reactance, inductive reactance, resistance, and conductance—make up the CHARACTERISTIC IMPEDANCE of a line. The voltage-to-current ratio at any point on a nonresonant transmission line is the characteristic impedance of the line.

The characteristic impedance does not vary with the length of the transmission line, but it does vary greatly with the size of the line and the amount of separation between the two conductors.

The characteristic impedance of a line is useful in determining the proper input coupling and output load for the line. If any other value than the characteristic impedance is used, energy is lost by being reflected at the mismatch.

In a coaxial line the characteristic impedance is expressed by the formula

$$Z_0 = \frac{138}{\sqrt{\epsilon}} \log_{10} \frac{b}{a}$$

where ϵ is the dielectric constant and $\frac{b}{a}$ is the ratio of the inner diameter of the large conductor to the outer diameter of the small conductor.

In a waveguide the characteristic impedance is called the wave impedance and it varies, depending on the size of the waveguide, the frequencies used, and the mode of operation.

MATCHING THE LOAD.—Energy that is reflected back along the line from a poorly matched load sets up standing waves along the transmission line. Standing waves on a transmission line are current and voltage loops (maximums) that are 90° out of phase with each other.

Remember the hemp line you tied to a rail? If you flip the loose end of the line so that the waves travel up to the rail and then are reflected back down the line to your hand, the rail is not "matched" to the line at the frequency. However, if the line extends indefinitely—is very, very long—then the wave travels down the line and, never reaching the end, never is reflected back to your hand. The wave traveling down the long line never sees anything ahead of it that appears to be anything but another length of line, so it continues down the line until it dies out naturally. If a shorter line is anchored to a lightweight spring wire at the rail it might be "matched" so that no wave would be reflected.

A traveling wave in a transmission line behaves in much the same way. If it comes to the end of the line and sees a load of different impedance, then it is reflected back along the line in standing waves. The voltages and currents in a transmission wave are always in phase, but the voltages and currents in a standing wave are always 90° out of phase.

On the other hand, if the traveling wave sees what looks like another length of transmission line—in other words, if the impedance of the load matches that of the line—then it continues until it is used by the load, just like the wave in the extremely long piece of line mentioned above. In this way, all the energy reaches the load, and none is wasted in reflections, or standing waves. As it is important to use every bit of available energy in the load, standing waves are to be avoided in a transmission line.

Resonant lines are lines that have standing waves. Therefore, the impedance of the load in a resonant line is not matched to the impedance of the line. A resonant line is always some multiple of a quarter wave in length.

A nonresonant line has no standing waves. Because standing waves are caused by a mismatch between the impedances of the load and the line, a nonresonant line must have a load impedance equal to the characteristic impedance of the line. In a nonresonant line, when the energy arrives at the load, the load appears as another section of transmission line. The load therefore absorbs all the energy, and none is reflected.

The job of matching impedances is important, not only because the impedance of the load, or antenna, must match that of the transmission line, but also because the impedance of the transmitter coupling must match that of the transmission line. For this reason, most transmission lines are provided with means for adjusting both the coupling to the antenna and the coupling to the transmitter. Short sections of transmission line often are used for this purpose. These sections are called STUBS. Two quarter-wave matching stubs are shown in figure 6-22. The stub is attached to the transmission line and may be either shorted or open at its base. A stub can change the impedance presented to the transmission line by changing the electrical length of the stub. If the stub is shorted the impedance is changed by moving the shorting bar on the stub, if unshorted, or open, by changing the physical length of the stub itself. The stubs may also be shifted along the line to produce an impedance match. By using stubs, you can change the effective load impedance to match the line at a particular frequency. If the frequency is then changed, a new adjustment will be necessary to make it nonresonant at the new frequency.

GROUNDED QUARTER-WAVE STUBS.—When a grounded quarter-wave stub is resonant, it acts like an insulator. Figure 6-23 shows a 2-wire transmission line using a grounded quarter-wave stub as an insulating support for the line. At points A and B, at the top of the stub, the impedance is high because the standing-wave current is minimum and the standing-wave voltage is maximum. From Ohm's law you can see that the impedance is maximum at these points since I is small and E is large. Because of this high impedance, no current flows from A to B through the stub. Thus, the stub acts as an insulator to r-f energy even though it is made of metal. Because the shorted end of the stub is a quarter wavelength away from the transmission line, its own low impedance at the base looks like a high impedance across the transmission line—that is, a standing wave can exist in the stub, with a voltage minimum at the bottom and a voltage maximum at the top. Do not confuse the standing wave in the stub with the traveling wave in the transmission line. They are two different things.

The Waveguide

You will remember that the waveguide is a rectangular hollow metal tube. The waveguide has lower r-f losses than any other common transmission line. The outside of the waveguide serves as a shield to prevent stray capacitive or inductive couplings. The waveguide, therefore, is ideal for use as a tranmission line in modern radars.

Lets's consider what happens in the waveguide.

Look again at figure 6-23. The grounded quarter-wave stub acts like an insulator across the line because the standing waves in the stub give it a high impedance at the top. Imagine for a moment that a second grounded quarter-wave stub is attached to the first, this time above the line as shown in figure 6-24. You now have a rectangle produced by the two stubs. Both stubs behave the same way electrically, so that the low

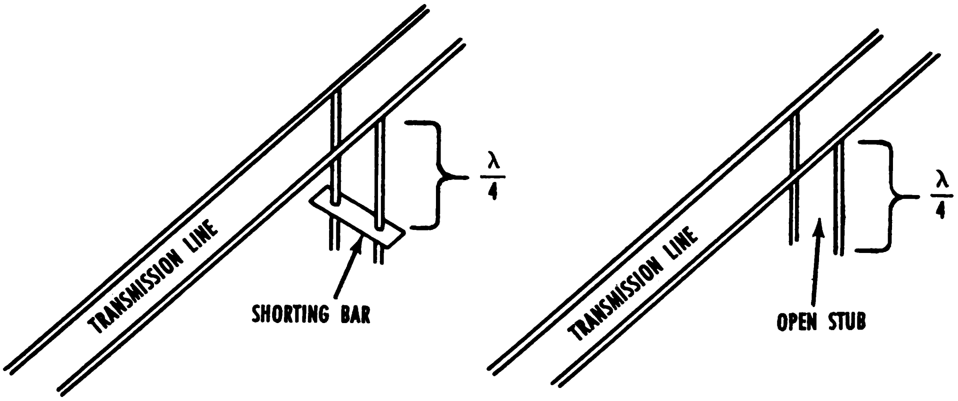


Figure 6-22.—Two quarter-wave impedance-matching stubs. 55.89

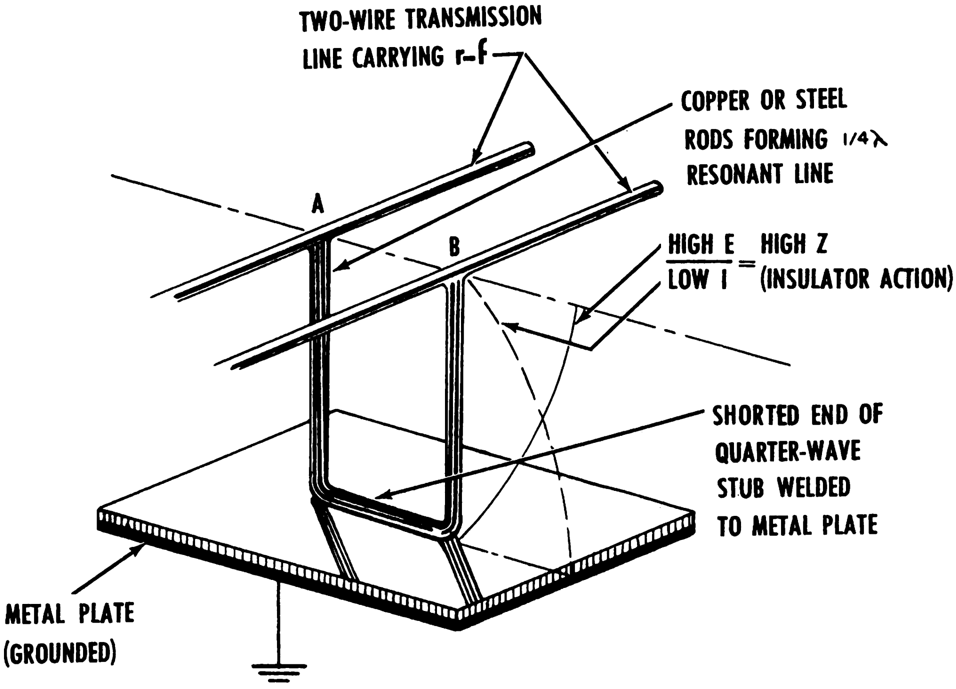

TWO-WIRE TRANSMISSION LINE CARRYING r-f
COPPER OR STEEL RODS FORMING 1/4λ RESONANT LINE
A
B
$\frac{\text{HIGH E}}{\text{LOW I}} = \text{HIGH Z (INSULATOR ACTION)}$
SHORTED END OF QUARTER-WAVE STUB WELDED TO METAL PLATE
METAL PLATE (GROUNDED)

Figure 6-23.—Two-wire transmission line supported by a grounded quarter-wave stub. 55.90

impedance shorting bars across both studs reflect as high impedances across the line. Therefore, the stubs do not affect the currents in the line.

Now stretch your imagination a little further and think of an extremely large number of these rectangular stub pairs placed along a section of transmission line. As these stubs touch one another the line begins to assume the shape of a rectangular hollow tube (fig. 6-25). The tube thus formed is the waveguide. It actually is made in long sections and not by placing a large number of stubs together, as we described it. However, the electrical properties of the waveguide are the same as if we made the waveguide from the stub pairs.

From the foregoing description, you can see that the waveguide must be in width at least a

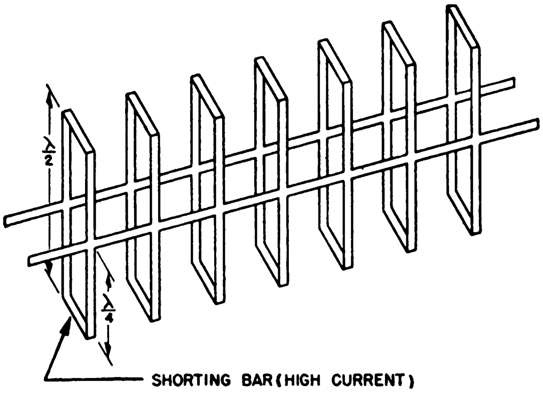


Figure 6-24.—Two-wire transmission line with grounded quarterwave stubs above and below the line. 55.91

half wavelength of the frequency it conducts because the stubs must be at least a quarter wave in length above and below the center line formed by the transmission line. If the waveguide is large enough we can see from the foregoing discussion that it will function as a transmission line.

CURRENTS IN THE WAVEGUIDE.—In waveguide transmission lines the electromagnetic fields may take any one of a number of configurations or modes. The simplest and most common mode in a rectangular waveguide is known as the TE_{10} mode (transverse electric wave, one maximum of the electric field in the wide dimension and no variation in the narrow dimension of the guide).

Figure 6-26 illustrates another method of analysis of waveguide operation. The case shown is for the TE_{10} mode of operation of a rectangular guide. Figure 6-26A represents two waves of the same relatively high frequency propagating down the guide in a series of reflections from the walls of the guide. Figure 6-26B is identical with figure 6-26A, except that the waves in the former are of a much lower frequency.

Study the figure carefully. The solid lines denote the crests of the electric field of the waves, and the dotted lines denote the troughs. The crest and trough are referred to in this chapter as follows: the crest is the instantaneous maximum positive of the E lines, and the trough is the instantaneous maximum negative of the E lines. Note that along the center line the crests of one wave meets those of the other and they will add. Similarly, note that the troughs likewise add. The result is that the two waves traveling at an angle to the walls of the guide combine to form a single wave traveling down the guide. Also note that along the walls of the guide the crest of one wave meets the trough of the other waves. The result is that the E lines of the combined wave are zero everywhere along the walls. (Actually the two waves are only one wave and the reflections of that wave.)

Notice λ and λ_G. The wavelength in waveguide is longer than the wavelength in space. The reason for this is apparent if one considers the fact that the two waves are moving with the speed of light in the directions shown in figure 6-26A, whereas the resultant wave is traveling in the direction of the guide. In this direction the wavelength (distance from crest to crest) is longer as shown by λ_G. By means of trigonometry it is easy to derive the relation between the free-space wavelength, λ, the guide wavelength, λG,

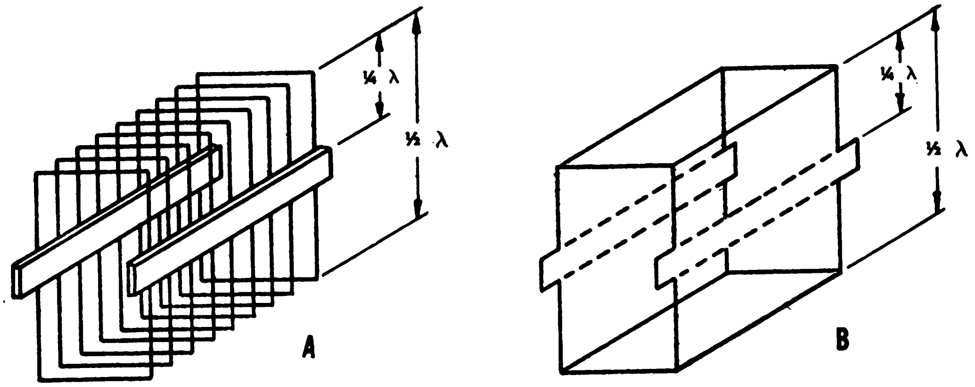
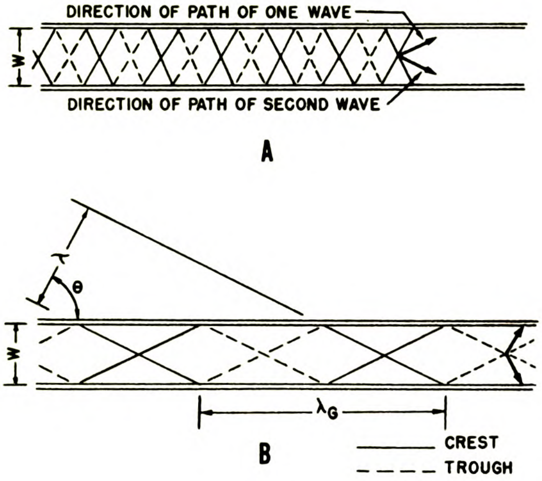


Figure 6-25.—Development of a waveguide from a large number of stub pairs. 55.91.0


DIRECTION OF PATH OF ONE WAVE
W
DIRECTION OF PATH OF SECOND WAVE
A
λ
θ
W
λG
B
CREST
TROUGH

A. Frequency well above cutoff
B. Frequency lower than that in A

Figure 6-26.—Analysis of waveguide operation, TE_{10} mode. 55.92

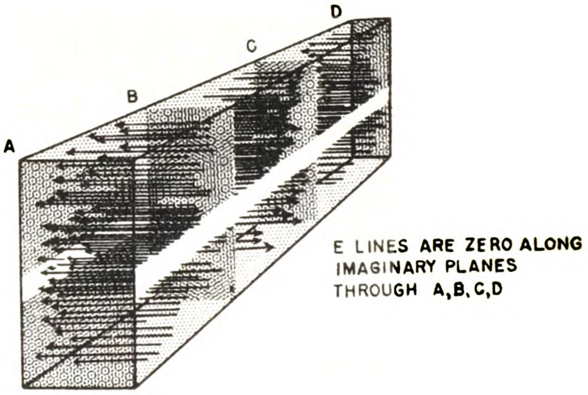


Figure 6-27.—E lines in a waveguide. 55.93

and the width, W, of the guide. The relationship between λG and λ is necessary to determine the phase velocity of the wave traveling down the guide. The phase velocity exceeds the velocity of light in most cases.

Figure 6-26B suggests that, as we go to lower frequencies (longer wavelengths) the two waves will move in a direction more nearly perpendicular to the walls of the guide and that λG will become very long. This is indeed the case. Below a certain frequency, called the CUTOFF FREQUENCY, the waveguide cannot propagate the wave. At this cutoff frequency the waves will be moving perpendicular to the walls and not down the guide. A study of figure 6-26B shows that this is the case when λ is equal to 2W.

Other modes of operation can be explained in a manner similar to the foregoing by assuming additional waves reflecting from the walls of the guide.

Figure 6-26A and B show a top view of the electric field (E) of two waves combining to form a single wave moving down the guide. Figure 6-27 shows this same field by means of a series of vectors. One direction of these vectors is arbitrarily chosen to represent the crest of the wave. The other direction then represents the trough. The direction of the arrows indicates the instantaneous polarity of the field. A study of figure 6-27 suggests that currents should flow in the walls of the guide because of the alternate electric polarities. This is indeed the case, and figure 6-28 shows the corresponding magnetic field (H) for the TE_{10} mode.

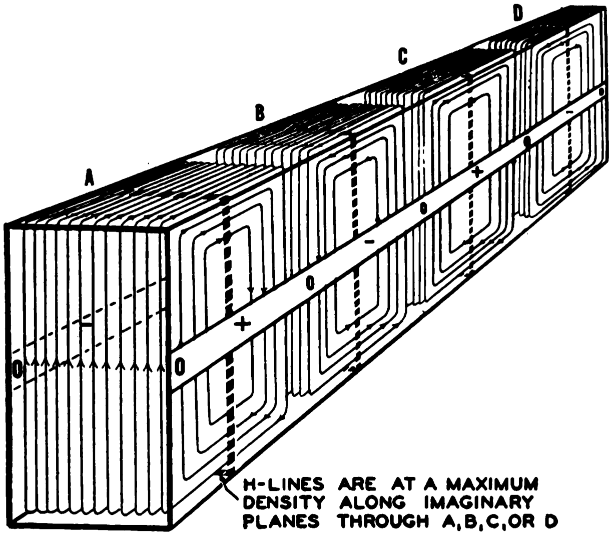
Figure 6-29 is a cross section of waveguide taken at a voltage maximum. Figure 6-29A shows the E lines only; figure 6-29B, the H lines only; and figure 6-29C, both E and H lines.

Figure 6-30 shows a longitudinal section of waveguide. Figure 6-30A shows the E lines only; figure 6-30B, the H lines only; and figure 6-30C, both E and H lines. This should give you a good idea of how the fields in the waveguide look.

Now that you have seen what the wave looks like when it is standing still in the waveguide, you can imagine the same pattern in continuous motion. To describe the pattern we have had to stop the wavefront at a particular point along the waveguide and look at it at that point. Keep in mind, however, that the wavefront never stops at any point but moves continuously down the waveguide.

SURFACE SLOTS ON A WAVEGUIDE.—If you want to insert a movable probe into a rectangular waveguide which is propagating a TE_{10} mode, the slot in which the probe travels must be taken lengthwise along the broad side of the guide. You can understand why a slot could not be taken lengthwise along the narrow side or across the width of the guide when you consider that this would open the current paths.

On the other hand, a narrow slot taken lengthwise down the center of the broad side of the guide disturbs neither the transmission line nor the currents which will flow along the edge of the slot. A narrow slot could also safely be taken across the narrow side of the waveguide


D
C
B
A
+
-
0
H-LINES ARE AT A MAXIMUM DENSITY ALONG IMAGINARY PLANES THROUGH A,B,C,OR D

55.94

Figure 6-28.—H lines in a waveguide.

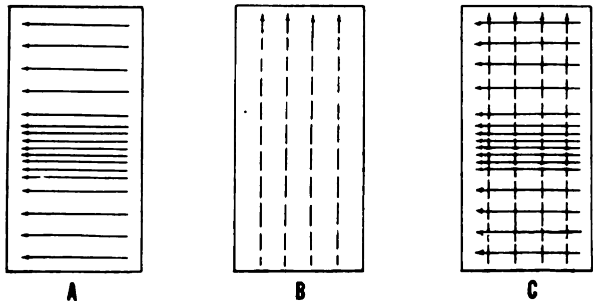


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Figure 6-29.—Cross section of a waveguide, showing electric and magnetic lines of force.

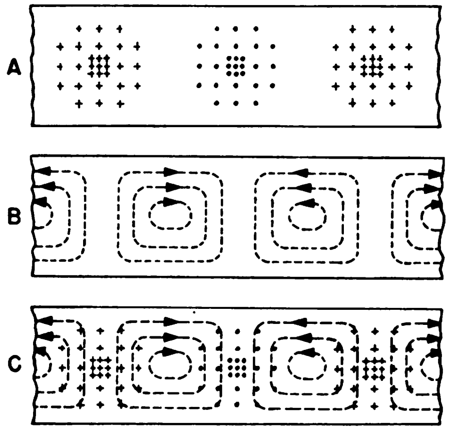
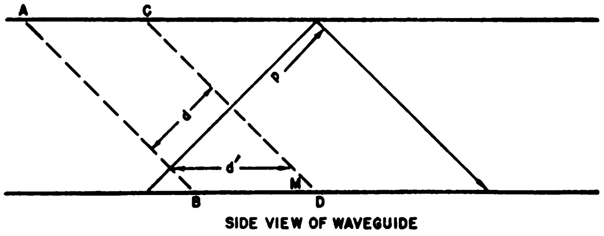


Figure 6-30.—Side view of a waveguide, showing electric and magnetic lines of force. 55.96

for the insertion of a probe or loop because the currents flow along the edges of the slot and the efficiency of the transmission line is not affected.

ACTUAL VELOCITY VERSUS PHASE VELOCITY.—How fast does the wavefront move down the waveguide? It appears to move faster than the speed of light, because if you measure a wavelength in the waveguide and the same wavelength in air the wavelength inside the guide appears to be longer. However, don't let this fool you, for the velocity of the wavetrain in the guide is not faster than light. What really happens is that the wave inside the waveguide is traveling at an angle. It bounces off first one side of the waveguide and then the other. The PHASE VELOCITY of the wave is greater than the speed of light, but the ACTUAL VELOCITY is less. Phase velocity is the velocity of a point on the wavetrain along the length of the guide. In figure 6-31, AB represents the leading edge of a wavefront, and CD represents the same wavefront after traveling a distance d. The path of the wave in the guide is along line p. At a measuring point, M, in the guide the wave appears to have traveled a distance $\underline{d}'$, although the wave actually has traveled only a distance d during the given time. This gives the effect of greater velocity, because the velocity formula is $v = \frac{d}{t}$. Time is the same for both actual and phase velocities, but the measured distance $\underline{d}'$ appears much greater than the actual distance d. Because of this effect, the length of a wave inside the guide is longer than the same wavelength in free space. The phase velocity is equal to the velocity of light times the ratio of the guide wavelength to the free-space wavelength.

SKIN EFFECT.—Because the middle of the waveguide carries the high voltages, you may get the idea that you can ground the outside of



55.97

Figure 6-31.—Comparison of actual and phase velocity of a wavetrain in a waveguide.

a guide and get a spark discharge. However, this is not true. At high frequencies, energy tends to travel in a very thin layer, or coating, of metal along the surface of the conductor. This is called the SKIN EFFECT. Accordingly, the high voltage travels in a thin layer of metal along the inside surface of the waveguide. The rest of the thickness of the waveguide wall acts as an insulator. A spark could be drawn from the inside surface of the waveguide but not from the outside surface. For this reason, the inside surface of the waveguide is often copper plated or silver plated. This improves the conduction because silver and copper are excellent conductors.

FREQUENCIES CONDUCTED BY THE WAVEGUIDE.—The waveguide can conduct frequencies with half wavelengths that are shorter than the length of its long side, but it cannot conduct frequencies with half wavelengths that are longer than the length of its long side. In other words, the waveguide can conduct frequencies that are higher—but not lower—than those for which it was designed.

As the frequency conducted by a waveguide decreases toward the cutoff frequency, the phase velocity of the wave increases and the actual velocity decreases until, at the cutoff frequency, the phase velocity is infinitely large and the actual velocity is zero. At this point the wave is just bouncing up and down in the waveguide and goes nowhere. Conversely, as the frequency increases above the cutoff frequency, the actual velocity increases and the phase velocity decreases.

WAVEGUIDE IMPEDANCE MATCHING.—Just as in an open-wire line, the impedance of the load can be changed by the addition of stub sections. Stub sections for use with waveguides are lengths of waveguide coupled to the main waveguide. They may or may not be tunable. Short impedance-matching sections sometimes are coupled to the main waveguide in order to match the impedance of the transmitter or antenna to that of the waveguide. These sections contain plungers or plugs that can be moved in or out to change the length of the section and therefore the impedance of the load. More will be said about these sections in the discussion of cavity resonators.

WAVEGUIDE INPUT COUPLINGS.—You probably are wondering how the energy sets into the waveguide to begin with. Lockback at figures 6-29 and 6-30, and notice the spots where the electric and magnetic lines of force are concentrated. As the magnetic lines are current produced and the electric lines are voltage produced, there are two ways that energy can be coupled into the waveguide. One way is by coupling a large current into the spot of highest concentration of magnetic lines, and the second way is by coupling a high voltage into the place of highest concentration of electric lines.

In the first way, shown in figure 6-32, a loop extends into the end or side of the waveguide, where the concentration of magnetic lines is greatest. The loop is turned so that the largest possible number of magnetic lines can pass through it. The loop acts like a current-fed antenna and sets up r-f fields in the waveguide like those shown in figures 6-29 and 6-30.

In the second way, shown in figure 6-33, a quarter-wave probe extends into the waveguide at the point where the highest concentration of electric lines should be. This probe serves as a voltage-fed antenna and sets up the r-f fields in the waveguide.

CAVITY RESONATORS.—Just as quarter-wave sections of transmission line are resonant circuits, quarter-wave sections of waveguide behave like resonant circuits at the frequency for

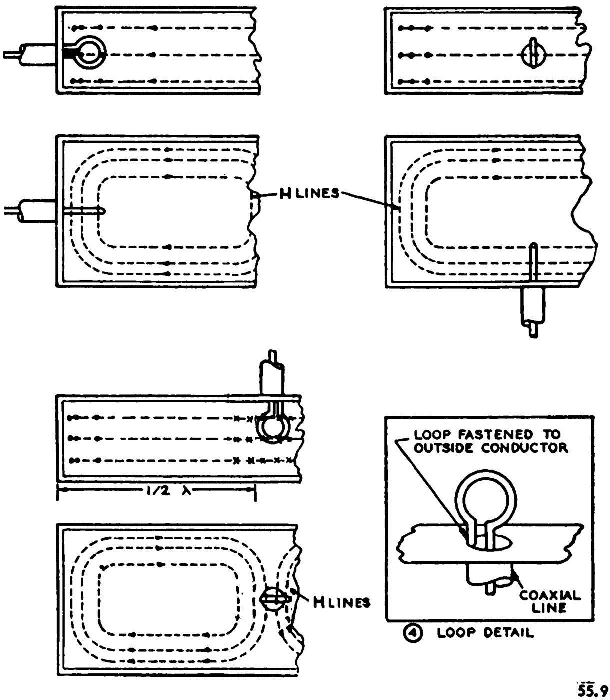


Figure 6-32.—Loop coupling in a waveguide.

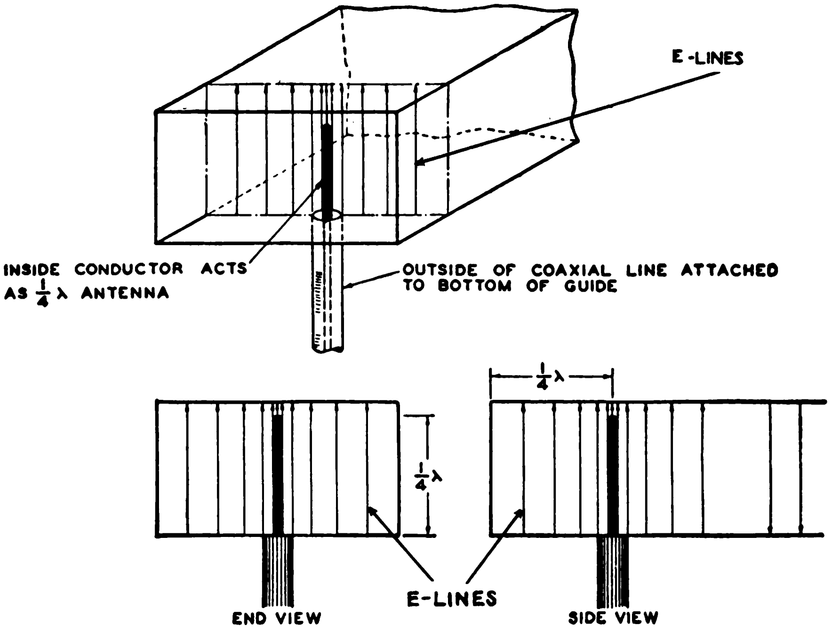

E-LINES
INSIDE CONDUCTOR ACTS AS $\frac{1}{4}\lambda$ ANTENNA
OUTSIDE OF COAXIAL LINE ATTACHED TO BOTTOM OF GUIDE
$\frac{1}{4}\lambda$
$\frac{1}{4}\lambda$
E-LINES
END VIEW
SIDE VIEW

Figure 6-33.—Probe coupling in a waveguide.

55.99

which they were designed. These sections are used for echo boxes, TR boxes, SWR indicators, and impedance-matching devices. Short sections of waveguide, or cavities, can be made to perform the functions of ordinary tuned tanks like those you studied in Basic Electronics, NavPers 10087-A. Even a closed tin can of the proper size behaves like a tuned tank at radar carrier frequencies.

As the size and shape of such cavities determine their electrical properties at a particular frequency, most of the cavities have tuning plugs or vanes that can be adjusted so as to perform efficiently.

Figure 6-34 shows two typical cavity resonators. Figure 6-34A shows a cavity used for wavelength measurements. Energy is coupled into the cavity from the main waveguide through the tiny slot at the end of the cavity. The r-f voltmeter reads maximum when the cavity is tuned to resonance at the radar frequency and the voltage probe is at a standing-wave maximum, as shown in the lower part of figure 6-34A. If either distance A or distance B is found in this way, the wavelength in the waveguide can be found by multiplying A by 4 or B by 2. However, remember that the wavelength in the waveguide is not the same as the wavelength in free space.

A devce similar to that shown in figure 6-34A is used in many radars to measure the standing-wave ratio in the waveguide. This is expressed as the ratio of the maximum standing-wave voltage to the minimum standing-wave voltage. A perfect standing-wave ratio (SWR) on a line with no standing waves is 1 : 1, or 1. This means that the line is flat; that is, there are no standing waves. A high SWR indicates a mismatched transmission line. The device that measures the SWR is called an SWR indicator.

The cavity in figure 6-34A is tuned by varying its size, which in turn varies the resonant frequency of the cavity. Figure 6-34B is a cavity that is tuned by varying the capacitance of the cavity. The tuning screw is attached to a metal disk (connection not shown) that is located at the point of maximum concentration of E lines. Varying the distance between the tuning screw disk and a disk on the cavity wall has the effect of varying the distance between the plates of an ordinary capacitor. Decreasing the separation of the metal disks therefore increases the capacitance and decreases the resonant frequency of the cavity. Increasing the separation has the opposite effect.

Other examples of tuned cavities were cited in the section on mechanical tuning of the magnetron-anode cavities.

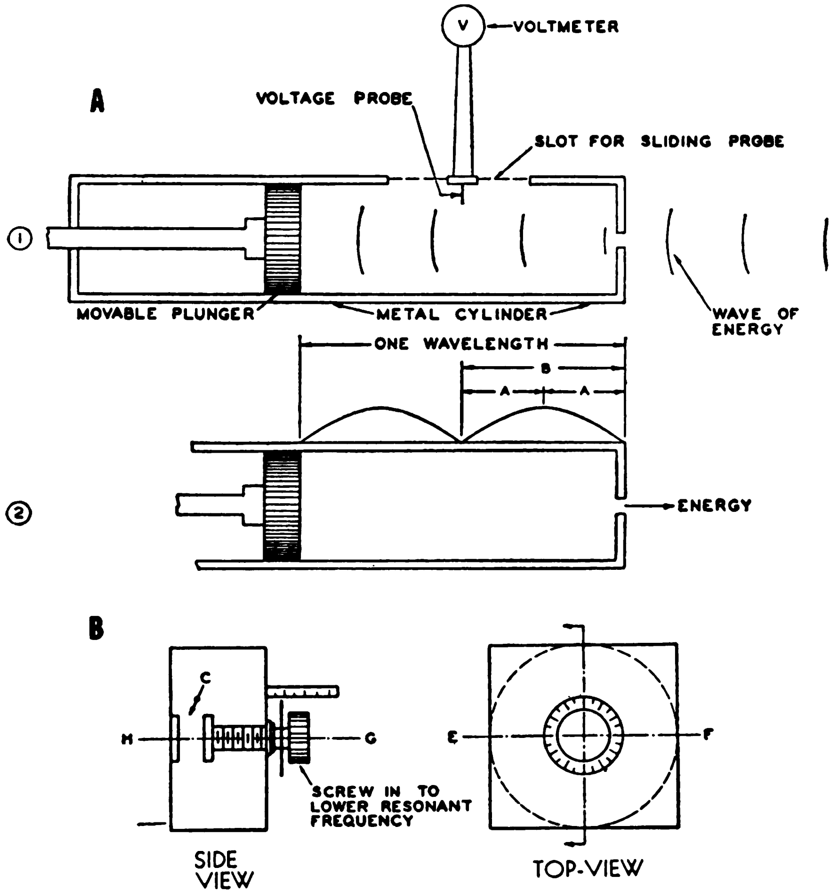
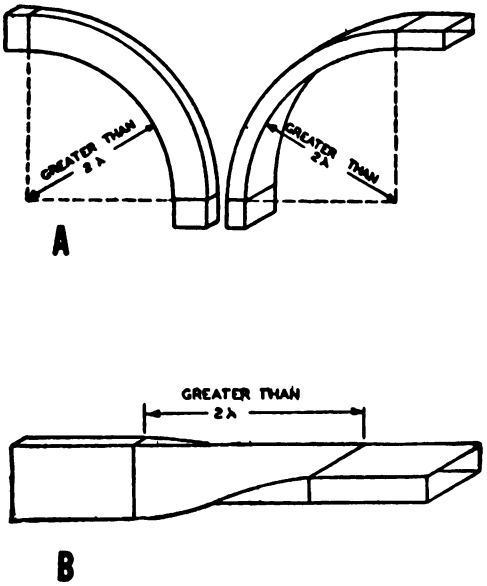


Figure 6-34.—Two typical cavity resonators. 55.100

BENDS AND TWISTS.—Most waveguides have bends and twists at some point along their length. In bending or twisting the waveguide, however, a few simple rules must be observed or a part of the r-f energy will be reflected. Two of the more important of these rules are: (1) The bend must have a radius greater and the twist must have a length greater than two wavelengths of the wave in the guide, and (2) the bend or twist must be smooth and regular rather than sharp or abrupt at any point.

Figure 6-35 shows two waveguide elbows, or bends, and one section of rotating, or twisting, the fields. You can see that in each of the three sections the bends are regular and have a radius greater than two wavelengths.

EXPANSION JOINTS.—Expansion joints, or choke joints, are used to permit the expansion or rotation of the waveguide. Figure 6-36 shows two different types of choke joints. Figure 6-36A shows a choke joint for use with a rectangular waveguide. In the cross-sectional view, notice the quarter-wave slots near the outside of the joint. These slots are located a quarter wavelength from the outside of the middle part of the guide where the fields are strongest. If energy from the waveguide attempts to escape at the joint, the quarter-wave slot resonates and presents a high impedance at point B. The high impedance at point B is reflected as a low impedance, or short circuit, a quarter wavelength away at point C. The short circuit effectively connects points E and D, thus presenting to the r-f fields an apparently unbroken waveguide. Although points P and Q in the end view of figure 6-36A are not a quarter wavelength away from the slot, little energy is lost because the r-f fields in the guide are weakest at these points. The r-f fields are strongest in the middle of the



55.101

Figure 6-35.—Waveguide bends and twists.

guide between the points M; you can see that the slot is a quarter wavelength away from these points.

A more efficient type of choke joint is shown in figure 6-36B. This type is used with a round waveguide as a rotating joint. One or both sections of the waveguide are free to turn without any substantial loss of energy at the joint.

If you examine the cross-sectional view in figure 6-36B, you can see that two quarter-wave slots are used, one in the top plate and one in the bottom plate. When r-f energy attempts to escape, these slots perform exactly like the single slot just described. They present a high impedance at their tops that is reflected as a low impedance to the waveguide sections a quarter wavelength away.

The end view of the choke in figure 6-36B illustrates a major advantage of the round waveguide joint. The slots are always a quarter wavelength away from the edge of the main guide, no matter how the sections are turned. This presents an apparently unbroken waveguide to the r-f fields at all points along the joint. Rectangular waveguides often have a short length of circular waveguide at the point where rotation is desired.

SLOTS AND PARTITIONS.—The impedance of a waveguide may be changed by the addition of metal partitions of various shapes inside the waveguide. These partitions can be designed to be inductive, capacitive, resonant, or attenuating.

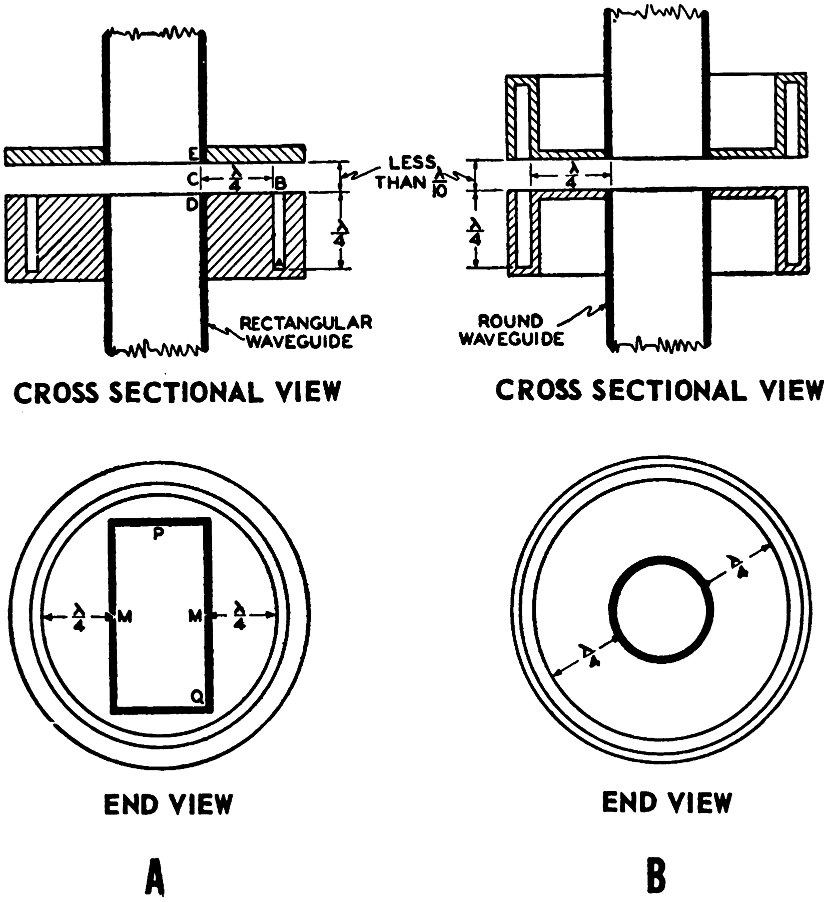
Figure 6-37 shows an example of each of the four types of partitions. If the slot is taken across the E plane, as in figure 6-37A, the E field sets up currents through the metal partition so that action is inductive. On the other hand, if the slot is taken across the H plane, as in figure 6-37B, the E lines are shortened and the partition is capacitive. In figure 6-37C a combination of the inductive and capacitive partitions sets up a slot with the electrical qualities of both. Therefore, the slot is resonant in its effect on the r-f fields. Such a slot can be designed to resonate at the carrier frequency and hence block the passage of r-f energy, or it can be made to couple r-f energy from one waveguide section to another.

Figure 6-37D shows a partition made of a resistive material placed lengthwise along the middle of the waveguide. This partition is in the E plane, and a part of the E field is conducted through the partition, thus reducing the strength of, or attenuating, the E field. Resistive material also is used when a waveguide or section of waveguide is terminated abruptly. The material is placed at the closed end so that it absorbs the r-f energy and prevents reflections.

SHORTED SECTIONS.—Shorted sections of waveguide are used as r-f chokes and impedance-matching devices. These shorted sections can be made to present either a high or a low impedance at the junction with the main waveguide. A shorted quarter-wave section presents an extremely high impedance at its resonant frequency to the main waveguide, thus creating an effective open circuit at that frequency. On the other hand, a shorted half-wave section reflects itself as a low impedance, or short, to the main waveguide. The effect of these sections of waveguide can be compared directly to the properties of quarter-wave and half-wave shorted stubs on an open 2-wire transmission line.

MAINTAINING THE WAVEGUIDE.—The Fire Control Technician has little to do with repairing the waveguide. Repairs are difficult and tedious and are seldom necessary if the waveguide has been installed properly. For this reason, we will discuss only a few general maintenance factors.

The waveguide must be kept clean, especially the inner conducting surface. Large quantities of dust, lint, or water inside the waveguide act as attenuators and lower the efficiency of the



A. Rectangular
B. Circular
Figure 6-36.—Waveguide choke joints.

55.102

radar. As the waveguide usually is closed, it is unlikely that particles of foreign matter will get inside the guide. If there is a low part of the waveguide run where water collects, a few small holes may be drilled in the guide. Should it be necessary to remove the waveguide, remove the sections of waveguide with great care, because a dent changes the impedance of the guide. Cover each open end immediately after removing a section so that no dust or other foreign matter can enter.

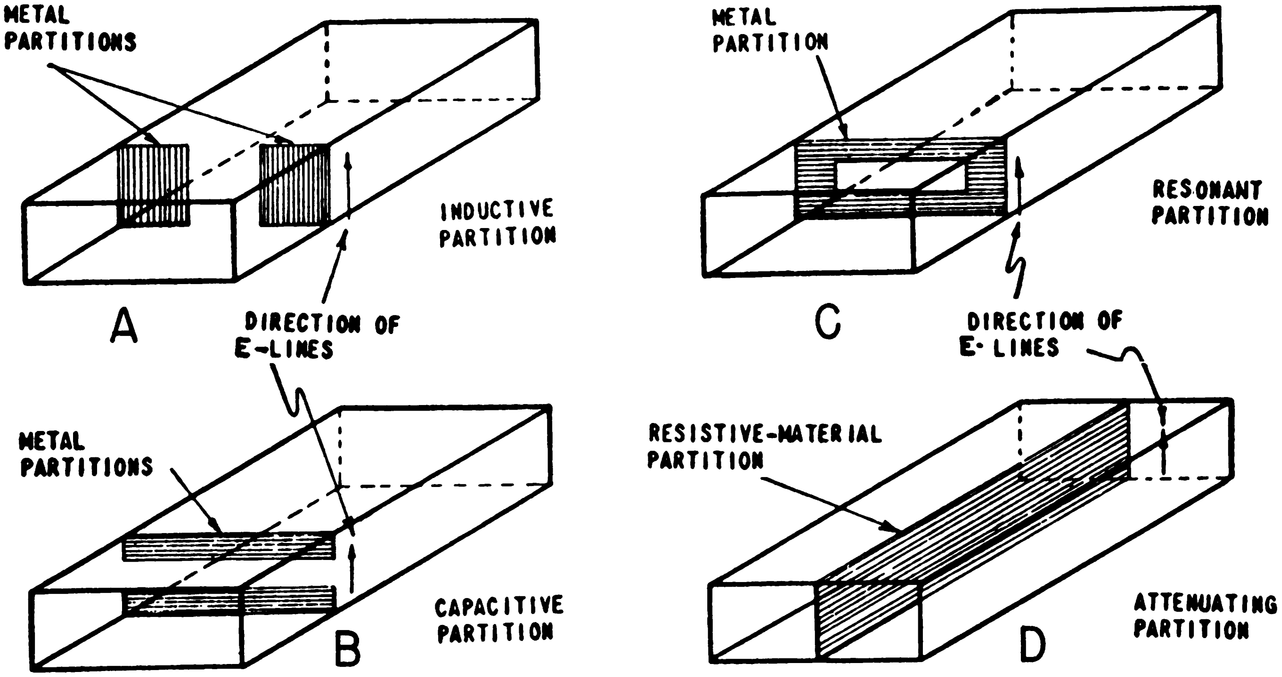
Dents or breaks in the waveguide should be repaired only by an expert metalsmith. If the waveguide is not perfectly smooth and true, large energy losses can result. In plated waveguides, the interior usually must be replated after any major repair that has damaged the old plating.

After each repair to the waveguide, you should measure the standing-wave ratio of the waveguide and adjust the coupling until the radar is operating at maximum efficiency.

You can see that repairs to the waveguide are complicated, delicate, and time consuming. In wartime, when it is necessary to remain at sea for long periods, repairs may be necessary, and you should know the general procedure for making them.

THE TR BOX

You have learned how the radar pulse was produced and coupled into the output line. In this discussion you will learn how the same r-f line is used for both transmitting and receiving.



A. Inductive
B. Capacitive
C. Resonant
D. Attenuating
Figure 6-37.—Waveguide partitions. 55.103

The simplest radar r-f system consists of the elements shown in figure 6-38. In this system there are two separate antennas—one for transmitting and one for receiving. Because there are two antennas, there are also two r-f lines, one connecting the transmitter to the transmitting antenna and the other connecting the receiver to the receiving antenna.

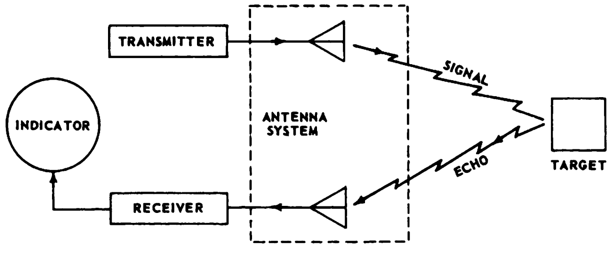
However, more practical systems use a single antenna for both transmitting and receiving, with a single r-f line coupled to both the transmitter and the receiver. With a single antenna, if the receiver is not protected from the powerful transmitter pulse the i-f stages will be saturated and blocked and the crystal destroyed. The receiver must be sensitive enough to respond to echo signals with power measured in micromicrowatts. Therefore, if the same line is used to carry the transmitted pulse of powers up to 1 megawatt, and if the receiver is not well protected, the powerful pulse will damage the receiver greatly.

The TR (transmit-receive) BOX, or DUPLEXER as it is sometimes called, is a switch that permits the same r-f line to be used by both the transmitter and the receiver. The main function of the TR box is to protect the receiver crystal from the high powered pulse.

TR Box—A Switching Device

The simplest form of TR device is an electrically operated double-pole double-throw switch in the r-f line like that shown in figure 6-39. The switch must be synchronized carefully with the PRF of the radar so that the proper channel is blocked at the proper time. This means that a relay-operated switch to operate with a radar having a PRF of 1000 pulses per second would have to make 1000 revolutions per second, or 60,000 revolutions per minute. A relay that operates for long periods at this rate is difficult to design and even more difficult to synchronize exactly with the time of the transmitter pulse. Because of these difficulties, motor-driven mechanical switches are impractical.

An electronic switch was designed to perform the function of the mechanical switch. This



55.104

Figure 6-38.—Radar with simplified r-f system.

electronic switch is the TR box that you find in modern radars. The TR box switches the line from the transmitter to the receiver just as does the double-pole double-throw switch in figure 6-39. The two switches differ chiefly in the way in which the switching function is performed. The TR box is simply a spark gap. It is carefully located in the receiver line an odd multiple of quarter wavelengths away from the main r-f line so that it arcs over during the transmitted pulse and reflects a high impedance to the top of the T formed by the junction of the main r-f line and the line to the receiver (point B). In figure 6-40 the TR box is located at point C a quarter wavelength from the main r-f line.

The TR box does not arc over for echoes coming down the r-f line to the receiver because the echo signals are so weak that they cannot break down, or ionize, the gap. Therefore, an incoming echo signal sees the base of the T (line BCD) as a half-wave line that is terminated in the receiver input impedance. When the echo reaches the T, it has a choice of two paths—one to the magnetron, which reflects a high impedance during its resting time, and the other to the receiver, which reflects only a low input impedance. Thus, most of the echo signal chooses the low-impedance path to the receiver.

When the magnetron or other type r-f oscillator fires, the high voltage pulse travels up to the T and down the receiver line as far as the TR box at C. The TR spark gap quickly ionizes and conducts, presenting a low impedance during conduction. This low impedance, or short, is reflected back to the T (point B) one-quarter wavelength away as a high impedance. The gap continues to conduct until the transmitter stops firing. At that time the gap deionizes and the line is ready to conduct the incoming echo signals. You can see that the base of the T represents a high impedance during the transmitter pulse. The high-power r-f pulse therefore selects the low-impedance path to the antenna rather than the high-impedance path to the receiver.

The speed of operation of a TR box is limited only by the time required to cause the gap to ionize and the time required to extinguish the arc, or deionize the gap. The ionization time usually is less than 1 microsecond. The deionization time, which usually is about 10 microseconds, is called th RECOVERY TIME of the box.

Anti-TR Boxes

In the example just described, coupling the echo pulse into the receiver branch depends on the increase in impedance reflected by the magnetron when it stops oscillating after each pulse. Because all radars do not have magnetrons that change enough in impedance at this instant, it is necessary to have a second TR box in these radars. The second TR box is located in the r-f line between the first TR box and the magnetron and is called the ANTI-TR (ATR) BOX. The anti-TR box blocks the path to the magnetron during resting time. The TR box itself blocks the path to the receiver when the magnetron is firing. Don't confuse the anti-TR box with the TR box.

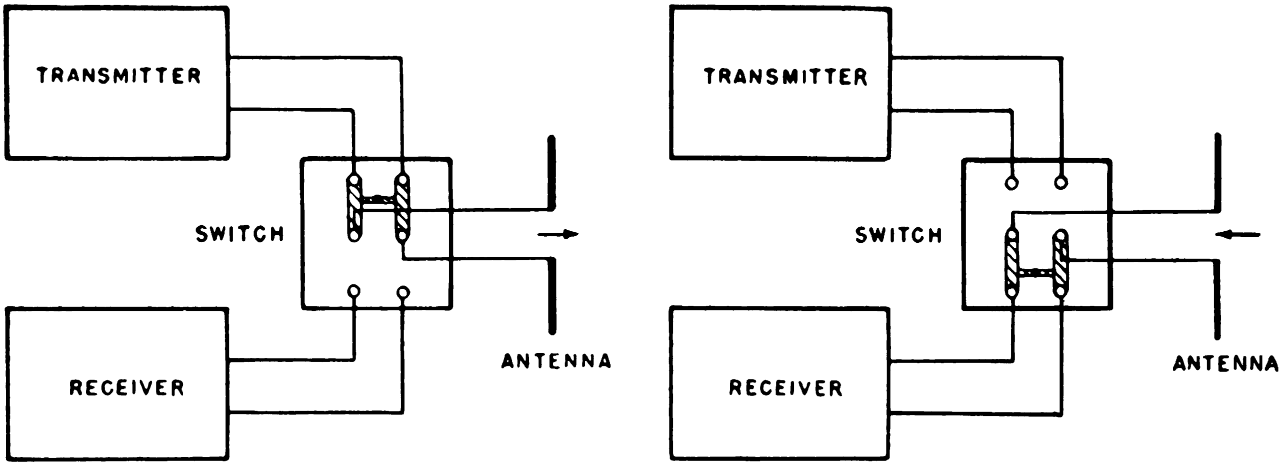
The anti-TR box is shown in figure 6-41. During the transmitted pulse both gaps B and E arc over and present a low impedance. This low impedance is reflected one-quarter wavelength away at the main line to points A and D as a high impedance. Therefore, the two branch paths are blocked to the transmitted pulse, and the high-power pulse must take the low-impedance path to the antenna.

After the magnetron has stopped firing, the gaps deionize quickly and the system is ready to receive incoming echo signals. An echo signal approaching the receiver T-junction sees a high impedance at the line to the transmitter. The shorted half-wave stub C in the anti-TR branch reflects itself as a high impedance at the receiver T (point D) three-quarters wavelength away, thus forcing the echo signals to take the low-impedance path to the receiver.

How Does the TR Look?

There are several types of TR box, ranging from a simple gap, which is formed by two electrodes placed across the line, to a gap enclosed in a partial vacuum with special electrodes to improve operation. The main operating requirements for a TR box are as follows:

1. It must have a high resistance before breakdown.



ANTENNA TRANSMITTING

ANTENNA RECEIVING

55.105

Figure 6-39.—Radar with single r-f line switched by mechanical double-pole double-throw switch.

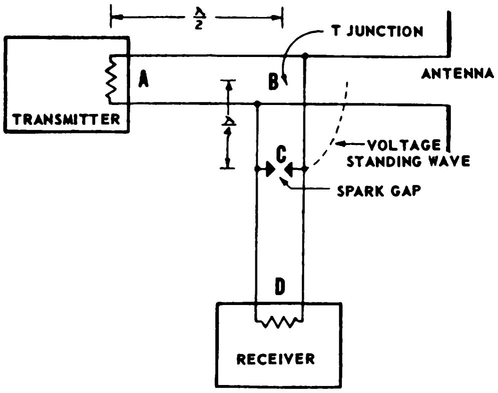


Figure 6-40.—R-f system using a TR box as a switching device. 33.119

2. It must have a low resistance after breakdown.
3. It must ionize, or break down, quickly.
4. It must deionize almost immediately after the end of the transmitter pulse.

The simple TR gap just mentioned can be used only with an open-wire line, and then not too efficiently. An air gap consisting of two electrodes across the line usually has a resistance of 30 to 50 ohms during conduction. This resistance is too high for efficient operation. The time required for the gap to deionize after firing is about 10 microseconds. Within 3 microseconds, however, the gap recovers sufficiently for half the power of the echo signal to get through to the receiver. This amount of power is usually sufficient for the receiver to operate. Yet very weak echo signals are absorbed by the gap and cannot get through to the receiver. During the 3 microseconds that the TR gap is completely blocked after the transmitter pulse, echo signals within a range of about 500 yards cannot possibly reach the receiver.

One way of speeding up ionization and deionization of a gap is by removing a part of the air or gas around the electrodes. The gap must be in a sealed glass or metal chamber (fig. 6-42).

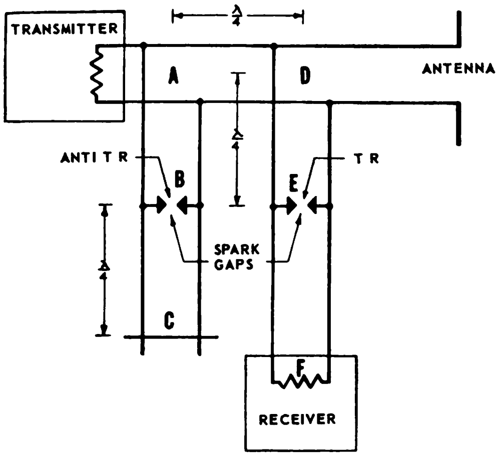


Figure 6-41.—R-f line with TR and anti-TR boxes. 33.120

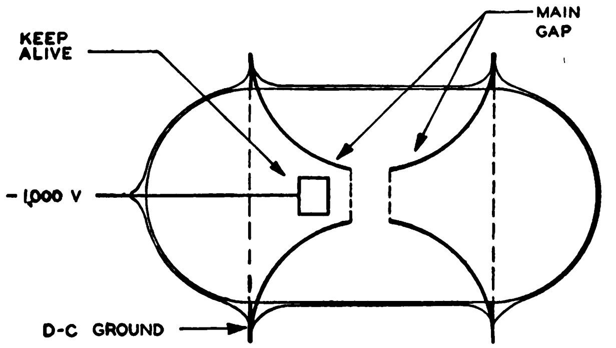


Figure 6-42.—TR tube with keep-alive electrode. 55.106

Some gas is placed in the TR tube in order to lower the breakdown voltage of the gap.

Another way of reducing the time required to break down the gap is to include a third electrode near the gap. This electrode is shown in figure 6-42. It is maintained at a constant negative potential of about 1000 volts. The electrode is called the KEEP-ALIVE electrode. Its purpose is to keep the gap partly ionized at all times. Thus, the transmitter pulse can break down the partly ionized gap much more easily.

Most TR boxes for use with microwave radars have resonant cavities. Most TR tubes are located INSIDE the resonant cavity. You can tune the cavity to resonate at the proper frequency by adjusting the screws on the outside of the cavity.

WAVEGUIDE COUPLING FOR TR TUBES

Coaxial Coupling

There are several ways in which a TR tube can be connected to a waveguide. One of the simplest ways is the coaxial coupling. A coaxial loop or probe extends into the waveguide and couples energy from the waveguide into the TR cavity. The cavity can be coupled to the receiver by a second coaxial loop or probe and a short length of coaxial line.

Slot Coupling

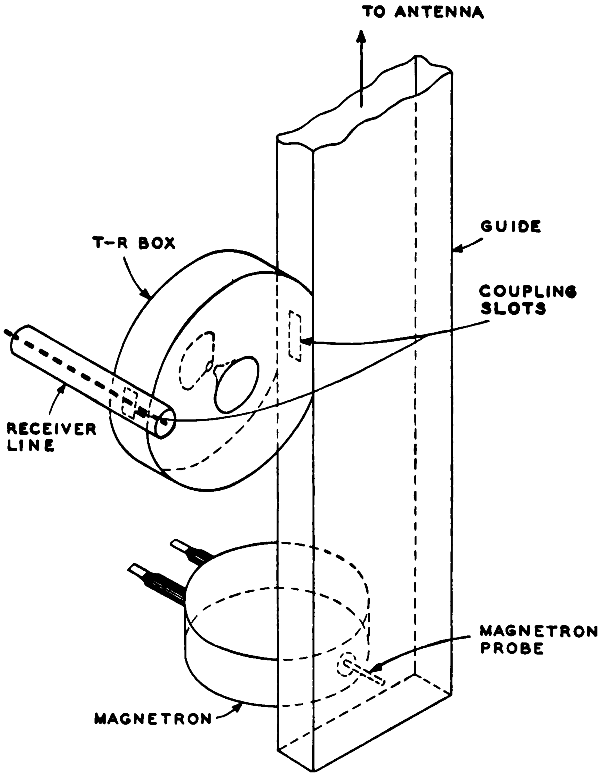


Figure 6-43.—Slot-coupled TR box. 55.107

Another way in which a TR tube can be connected to a waveguide is by means of a slot on the side of the waveguide (fig. 6-43). The slot can be constructed to act as a capacitor or as an inductor at the radar carrier frequency, depending on its dimensions. A portion of the transmitter pulse is coupled into the TR cavity through the slot, where it breaks down the gap. This makes the cavity nonresonant and reflects a short circuit across the slot. This effectively closes the slot to the transmitter pulse while the gap is firing. An echo signal, on the other hand, sees a high impedance in the transmitter line created either by the increased impedance of the magnetron or by an anti-TR section. It therefore passes through the slot, which now presents a low impedance because the gap is deionized. The echo signal passes through the TR cavity and out the other side. Figure 6-43 shows a coaxial-cable receiver output line, but the output line also can be another waveguide section.

Coupling

Still another way of coupling the TR cavity to the waveguide is by means of a T-junction, shown in figure 6-44. The T-junction is a section of waveguide in the shape of a T. In most

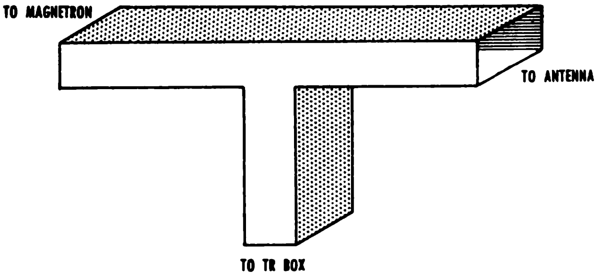
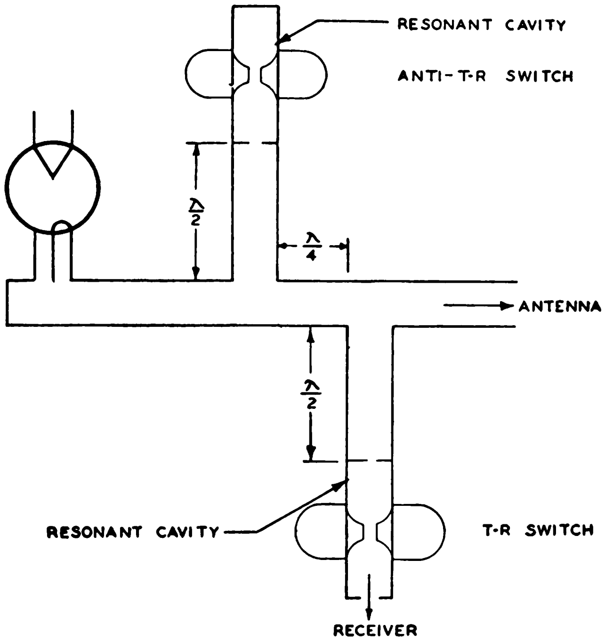


Figure 6-44.—Waveguide T. 55.108

r-f lines the signal is coupled into the TR arm of the T and then is fed a few half wavelengths down through a slot into the TR cavity. A second slot below the cavity couples the TR cavity to the receiver. A circuit employing two T-junctions—one for the TR cavity and the other for an anti-TR cavity—is shown in figure 6-45. When the transmitter is pulsed both the TR and ATR gaps break down and reflect a short circuit at the T-junctions. Therefore, the transmitter pulse is caused to continue along the line towards the antenna.

When the transmitter is deenergized the gaps become open circuits. The ATR line then reflects a short circuit at the TR line T which is three-quarters wavelength away from the high impedance of the resonant cavity on the ATR line. The received echoes cannot enter the transmitter line and therefore follow the line to the receiver. The cavity on the receiver line is designed to match the impedance of the line when the TR tube is not fired.



55.109
Figure 6-45.—Waveguide using two T-junctions.

THE RECEIVER

The receiver of a radar detects the tiny echo signal coupled to it through the r-f line and amplifies the signal many times. As the radar pulse is extremely weak, the receiver must have a very high gain to produce an output signal of the required voltage. The signal cannot be amplified readily at the carrier frequency because: (1) The carrier frequency is variable and the amplifier stages would have to be tunable, and (2) the carrier frequency is so high that you cannot get amplification from standard tubes. For these reasons, the echo must be heterodyned to lower frequencies during the course of its amplification.

You know that the radar receiver is of the superheterodyne type, like many of the Navy's communications receivers. However, there are significant differences between the radar receiver and the communications receiver. One difference is the higher gain required by the radar receiver. Another is the wide bandwidth of the radar receiver as compared to the relatively narrow bandwidth of a communications receiver. A physical difference that results from the high gain and the wide bandwidth requirements of a radar receiver is the increased number of amplifier stages.

Tuning is difficult in some radar receivers because of the tendency of the r-f oscillator and the receiver local oscillator to stray from their set frequencies. To compensate for these frequency changes, most radar receivers have an automatic frequency control (AFC) circuit that keeps the local oscillator on the beating frequency that produces the correct intermediate frequency.

OVERALL REQUIREMENTS AND LIMITATIONS

Gain

The ordinary communications receiver picks up signals from a primary radiator—that is, those signals that are radiated directly from the antenna of the transmitter. Therefore, the received signal is relatively strong and is continuous. The radar receiver, on the other hand, must pick up a small portion of a pulse signal that is reflected from an unenergized surface—sometimes very small—in the path of transmitter radiation. The strength of the echo signal usually ranges anywhere from 0.5 microvolt to several microvolts, depending on the strength of the transmitter pulse, the size of the target, the size of the antenna, and several other factors.

Indicators using type-A scopes require an output of 40 to 100 volts for a 1-inch deflection on the face of the tube. Type B and type PPI scopes use intensity-modulated scans that require about 20 volts to raise the grid potential of the indicator tube above cutoff. Therefore, to get an output potential sufficient to make a meaningful indication on the indicator scope, high gain is required from the radar receiver. In most radar receivers the gain is about 100,000,000.

Bandwidth

A radar pulse is composed of a wide band of frequencies, and to preserve the shape of the original pulse in reception the bandwidth of the receiver must be wider than the band of frequencies contained within the pulse. Figure 6-46 shows the effect of narrow, medium, and wide bandwidths on a received pulse.

Furthermore, the scattering of a radar pulse by the target uses up so much of the pulse power that the returning echo is of extremely low power. Therefore, a wide bandwidth also is necessary in order to receive a maximum amount of echo power, because the echo power is distributed about the sidebands of the original transmitted pulse. A receiver bandwidth that is too wide, however, permits too much noise to be amplified.

Most communications receivers have bandwidths of a few kilocycles. The bandwidths of radar receivers, however, range from 1 megacycle to 5 megacycles. The gain of the radar receiver should be as uniform as possible over the entire bandwidth; otherwise, the output signal becomes distorted or misshapen.

Distortion

Distortion, or poor reproduction of the pulse shape, is closely related to the bandwidth of the receiver. If the bandwidth of a radar receiver is small and the pulse duration short, the echo pulse is distorted in the receiver. Thus, the resulting waveform on the indicator scope also is distorted. Distortion due to narrow bandwidths is shown in figure 6-46, B and C. Range is measured on the face of the indicator by the time interval between the transmitted pulse and the returning echo. Therefore, if the echo is distorted, the indicated range is likely to be inaccurate.

A certain amount of distortion must be accepted because amplification varies slightly at different frequencies within the bandwidth and because the bandwidth of the receiver does not contain all the pulse harmonics. Harmonics in a radar pulse are like harmonics in a musical tone. They are frequencies that are multiples of the pulse repetition frequency. Less power is contained in the harmonics that are farthest away from the center or carrier frequency, so some of them can be cut out without great loss of power or distortion. Furthermore, to increase the bandwidth enough to contain all the harmonics of the pulse would allow the receiver to amplify so much noise that the decreased amount of distortion would be outweighed.

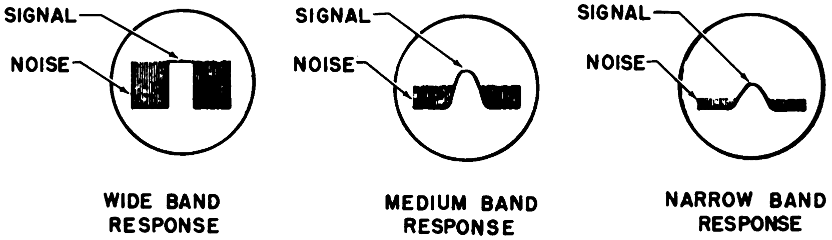


Figure 6-46.—Effect of bandwidth on shape of received signal. 55.110

Tuning

Since the magnetron and the receiver local oscillator often drift from the proper frequency, some means of tuning is necessary. An automatic frequency control (AFC) is used in most radars to compensate for frequency variations. The AFC circuit causes the local oscillator to follow variations in magnetron frequency so that the intermediate frequency (difference frequency) is kept constant. Most AFC circuits consist of a frequency discriminator connected to one of the i-f stages. The discriminator converts frequency variations from the standard into voltage variations.

The voltage variations are used to control the frequency of the receiver local oscillator. When the correct intermediate frequency is reached, the discriminator output becomes zero. AFC circuits will be discussed more completely later.

Blocking

Blocking occurs when an extremely large signal is fed into the receiver input. One or more of the i-f amplifiers is overdriven by the large signal, and the grid draws current. The grid current charges the coupling capacitor between the stages to a high level, producing a heavy bias on the grid of the amplifier. Until the large bias can leak off the capacitor, the amplifier cannot respond to small signals. Echoes from small targets or from targets at long range are hidden until the blocking voltage can leak off.

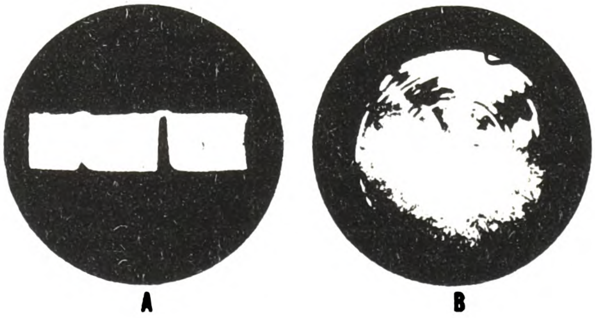
The recovery time of a blocked stage depends on the RC time constant of the charged coupling capacitor. It may range from a few microseconds to several hundred microseconds. Blocking usually is caused when a portion of the transmitter pulse leaks into the receiver line. In this case, echoes from close range cannot be seen because the receiver is blocked for a few microseconds after each transmitter pulse. This type of blocking is prevented in most radars by careful tuning of the TR devices and by a receiver gate voltage that keeps the receiver inoperative until a few microseconds after the transmitter has fired.

Noise

The wide bandwidth and the high gain of a radar receive require that noise be kept to a minimum. Any noise picked up in the initial receiver stage is amplified by the full gain of the receiver, just as is the signal itself. Atmospheric noise, static, and most other external noises that make up the major part of the noise in an ordinary communications receiver are so small as to be relatively unimportant because of the extremely high frequencies of most modern radars. However, some random noise is present in the receiver input itself, and this type of noise is extremely important because it is amplified by the full gain of the receiver. Noise in later stages through the receiver becomes less important because the signal is stronger in the final stages.

Noise shows itself on the indicator scope in different ways, depending on the type of indicator presentation. Figure 6-47 shows two ways in which noise can appear. Figure 6-47A shows noise as it appears on an A-type scope. This type of scope shows noise as a constantly changing field of noise "pips." This noise looks like a field of high, waving grass and consequently is known as "grass." Signals appear as steady pips in the moving "grass." Figure 6-47B shows noise as it appears on a PPI-type scope. The noise shows up as clusters of cloudy points of light that follow the sweep like a fading smear. These points of light move about and appear at random on the sweep. Noise on a PPI scope is called "clutter." Signals on the PPI scope show up as steady spots of light, which recur with each sweep in approximately the same position on the scope.

SIGNAL-TO-NOISE RATIO.—The extent to which a receiver amplifies noise, as compared



A. A-scope presentation
B. PPI-scope presentation
Figure 6-47.—Effect of noise on scope indications.

55.111

to amplification of the signal, is expressed as a figure known as the SIGNAL-TO-NOISE RATIO. This ratio is the power in the signal over the noise power in any part of the circuit. Thus, if the signal-to-noise ratio is high, signal reception is good. As the ratio approaches 1, the noise is amplified just about as much as the signal, and reception is poor.

The signal-to-noise ratio usually denotes the overall noise level for the receiver. However, it may denote the noise level for any signal stage or group of stages in the receiver.

HOW RADAR RECEIVERS WORK

Now that you know the general requirements and limitations of a radar receiver, you probably wonder just how they influence actual receiver circuits. A description of a typical receiver circuits and how they work is given here. Figure 6-48 shows the layout of a radar receiver. The signal passes from the waveguide or coaxial line through (1) the mixer, (2) the i-f preamplifier, (3) the i-f amplifier, (4) the second detector, and (5) the video amplifier. Of the circuits just listed, the i-f preamplifier is not always used in modern radar equipment.

Crystal Mixer

The signal from the antenna system is fed to the mixer. Most mixers are rectifying crystals. The crystal mixer provides the nonlinear impedance necessary for heterodyne action. The beating frequency from the local oscillator beats against the echo signal and creates an intermediate frequency between the radar carrier frequency and the local oscillator frequency. Intermediate frequencies have been standardized to a certain degree. They are usually 15, 30, and 60 megacycles per second.

Mixer Assembly

The mixer assembly, shown in figure 6-49, consists of two mixers—a receiver mixer and an AFC mixer. The inputs to the receiver mixer are received radiofrequency and local oscillator radiofrequency. Its outputs are the two input frequencies plus their sum and difference frequency. However, only the difference frequency is retained and used by the i-f amplifier.

The AFC mixer receives a greatly attenuated sample of the transmitted radiofrequency and the local oscillator radiofrequency. Its output is the same as that of the receiver mixer. Also, the AFC circuit only uses the difference frequency which controls the action of the AFC circuit.

The local oscillator shown in figure 6-49 is a conventional klystron with a single-tuned cavity. Its output frequency is controlled primarily by the mechanical tuning of the cavity. It can be controlled over a smaller range by varying the repeller plate voltage.

A simplified schematic of the mixer is shown in figure 6-50. The mixer assembly consists of two balanced dual mixers which utilize short-slot hybrids and balanced crystals detectors. Received radiofrequency from the duplexer travels through waveguide sections to the hybrid of the receiver mixer where the radiofrequency (represented by line A) splits equally to be detected by the diodes CR1 and CR2. The continuous wave from the local oscillator travels

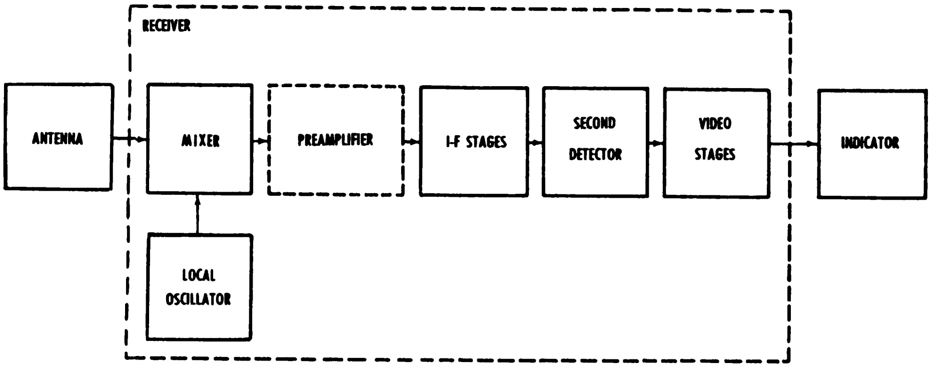


Figure 6-48.—Block diagram of a radar receiver.

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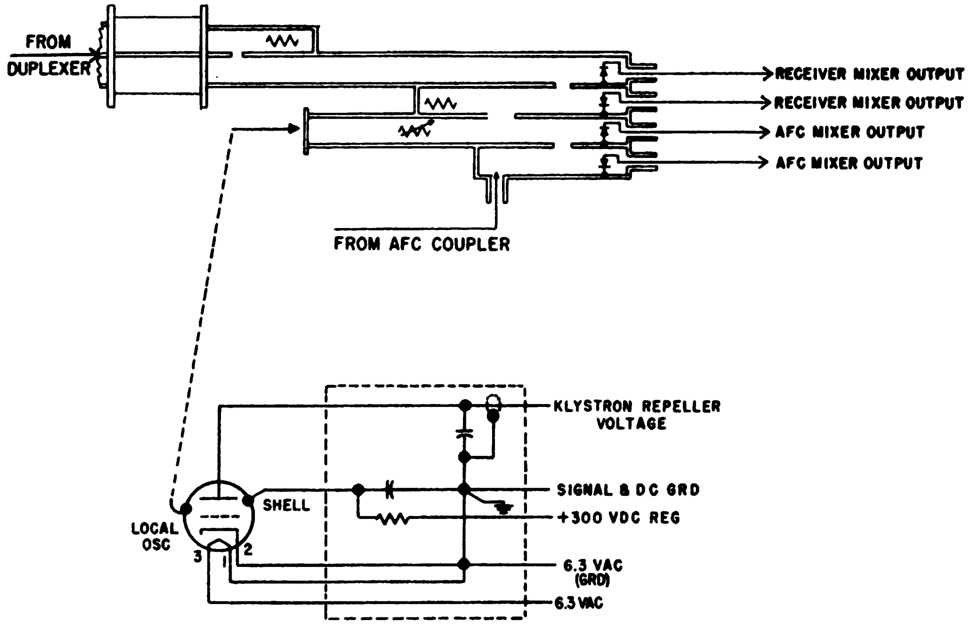

Figure 6-49.—Mixer assembly. 55.113

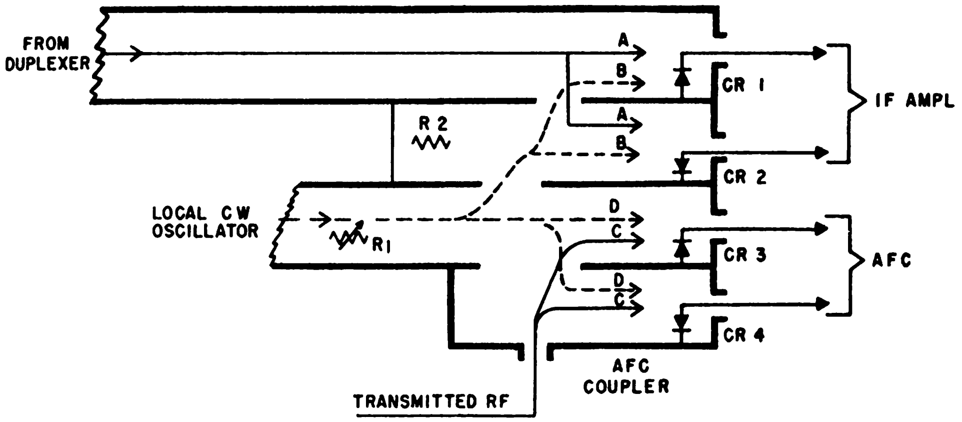

Figure 6-50.—Simplified mixer schematic. 55.114

through a different section of waveguide past the variable attenuator R1 where the radiofrequency is partly attenuated. At this point the local oscillator radiofrequency is split, with approximately half entering the receiver mixer and the remainder entering the AFC mixer.

The radiofrequency from the local oscillator entering the receiver mixer is again divided, with half being impressed on each diode CR1 and CR2.

NOTE: CR1 and CR2 are one-half wavelength apart in time required for both the received and local oscillator radiofrequency to reach each diode. Thus, they act like a balanced detector producing a maximum output signal with a minimum of noise. Their full wave output provides a 30-mc signal to the i-f amplifier.

The inputs to the AFC mixer are the local oscillator output and a small sample of the transmitted radiofrequency. The sample of the transmitted radiofrequency (C in figure 6-50) travels through the AFC coupler to the hybrid where it splits equally to diodes CR3 and CR4. The local oscillator radiofrequency (D) also splits equally to the diodes. The local oscillator continuous wave combines with the transmitted radiofrequency in diodes CR3 and CR4 to produce a difference frequency of approximately 30 megacycles. The output of the AFC mixer is coupled to the AFC circuit. A brief discussion of how the AFC circuit operates will be given later.

I-f Amplifiers

As you have already learned something about the operation of the mixer and the local oscillator, the only new element introduced by the i-f amplifier is the i-f strip.

In a radar receiver the major part of the gain is obtained in the i-f stages. As the i-f amplifiers operate at a much lower frequency than the r-f amplifiers, the gain can be much greater per stage. I-f amplifiers are more susceptible to regeneration, or oscillation, than video amplifiers, but they are less susceptible than r-f amplifiers. Oscillation can be avoided in i-f amplifiers by proper design, shielding, and decoupling of the stages. However, i-f amplifiers are not as susceptible to blocking as are video amplifiers, because inductors can be used in place of the grid-leak resistors necessary with video stages. The use of inductors permits a short recovery time from a blocking signal. Gain-control circuits can be used more easily in the i-f stages than in the other amplifier stages.

Despite the slightly greater noise level and increased difficulty of tuning with high intermediate frequencies, the intermediate frequency should be as high as possible. Two reasons for this are: (1) High intermediate frequencies give better image rejection, and (2) they permit the use of smaller tuning coils and bypass capacitors. In addition, the local oscillator is less likely to lock on the wrong side of the signal if the intermediate frequency is high. For example, suppose the tuning range of a local oscillator with automatic frequency control is 100 megacycles per second. If the local oscillator normally operates 60 megacycles per second above the signal frequency, then to lock on the wrong side (60 megacycles below the signal frequency) involves a frequency change of 120 megacycles per second. As the tuning range of the local oscillator is only 100 megacycles, it cannot lock below the signal. If the intermediate frequency were 15 megacycles, a frequency change of only 30 megacycles would permit the local oscillator to lock on the wrong side.

TUNING.—I-f amplifiers are tuned to amplify a relatively broad band of frequencies centered at the intermediate frequency. To achieve this tuning, either one or two resonant circuits are used in coupling each stage of the amplifier. If one resonant circuit is used in interstage coupling, the stage is said to be SINGLE TUNED; if two resonant circuits are used the stage is DOUBLE TUNED.

Single-tuned amplifiers have the advantage of being easier to tune than one with double-tuned stages. Since ease of tuning is extremely important in the field, single-tuned stages are widely used in Navy radar receivers.

Double-tuned amplifiers have the same gain and bandwidth as single-tuned amplifiers having the same total number of tuned circuits. The bandpass of both single- and double-tuned amplifiers may be made to have a flat top and steep edges—an important factor in radar receivers. However, double-tuned circuits are difficult to realign. The wide bandpass characteristic required in radar receivers can be obtained easily by stagger tuning of a series of single-tuned i-f stages.

Response Curves

The gain of a receiver over its pass band is shown in a graph of gain versus frequency. This graph is called a RESPONSE CURVE. The overall response curve of a receiver is the sum of the response curves for the individual amplifier stages in the receiver if the gain is plotted in decibels.

SPECIAL RECEIVER CIRCUITS

Superheterodyne Receivers and AFC

Radar receivers today universally employ the superheterodyne circuit to convert microwave signal frequencies to a frequency low enough to be amplified by standard r-f amplifier circuits operating at high sensitivity and selectivity. However, because of the large conversion ratio from the input signal frequency to the intermediate frequency, and other special requirements of the radar receiver, the mixer and local oscillator stages employ circuits radically different from those you have been used to seeing in conventional superhet receivers.

In the superheterodyne receiver that you studied in Basic Electronics, NavPers 10087-A, stations were changed by rotating the rotor of the variable ganged tuning condenser. This changed the resonant frequency of the tuned circuit in the r-f amplifier stage to the frequency of the desired station, and changed the local oscillator frequency by the same amount to maintain the required intermediate frequency. The intermediate frequency was amplified and detected. The detected audiofrequency was amplified and used to drive a speaker. If a station was on 1050 kc, the r-f amplifier was tuned to 1050 kc and the local oscillator was tuned to 1506 kc, producing an intermediate frequency of 456 kilocycles. (See figure 6-51.) These frequencies are much lower than the frequencies used in radar, but the receiver principles are the same.

The block diagram of the superheterodyne receiver used in a radar is very similar to that used in a standard broadcast receiver. In figure 6-51 you will note that the frequency to be received is 9000 megacycles. No r-f amplifier is used because of the problems involved in the amplification of so high a frequency. The received radiofrequency is coupled from the antenna to the converter, where it is mixed with a frequency of 60 mc higher to produce the desired intermediate frequency of 60 megacycles. This frequency at 9060 mc is generated in a special type local oscillator called a reflex klystron. It works on the same basic principle as the 2-cavity type discussed earlier. However, the reflex klystron has only one cavity. The first detector in a radar receiver is a crystal, but in the broadcast receiver you used a vacuum tube. The 60-mc intermediate frequency is amplified in the i-f stages and applied to the second detector. The output of this detector will be voltage pulses with a duration equal to the echo pulse from the target, and will reoccur at the PRF of the radar. If you listened to this signal with a pair of earphones, you would hear a signal at the frequency of the PRF. To make the output of this detector usable, it is amplified and presented on a cathode-ray tube.

In a broadcast receiver, the output intelligence is audio. In a radar the output intelligence is video (presented on a radar indicator tube).

The big differences between these two superheterodyne receivers are in the local oscillator and converter (mixer). You are familiar with these two parts of your superheterodyne receiver. Figure 6-52 shows these two parts of a radar receiver.

In the diagram, the local oscillator is a type 2K25 klystron. This oscillator is tuned

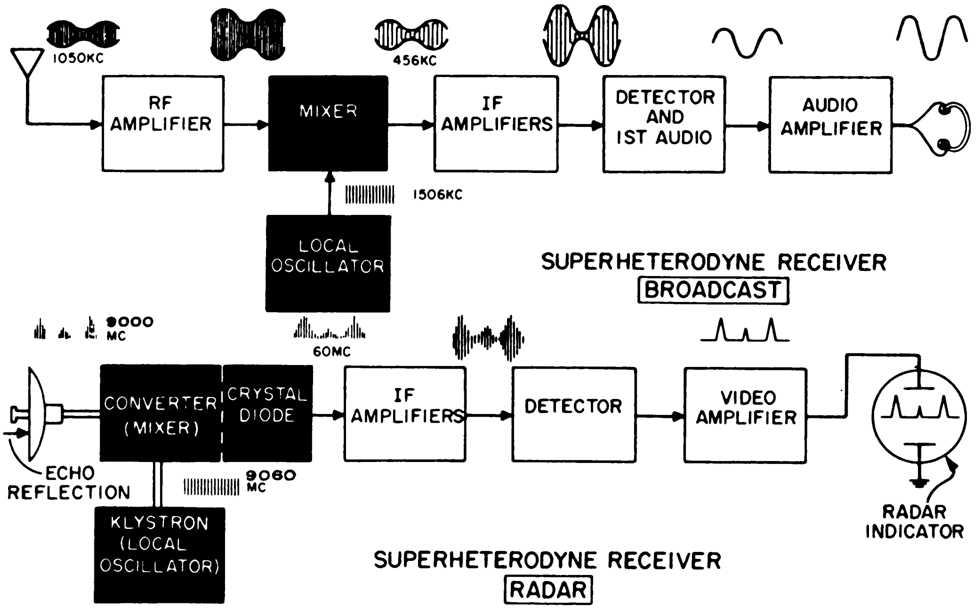

Figure 6-51.—Broadcast receiver and radar receiver compared.

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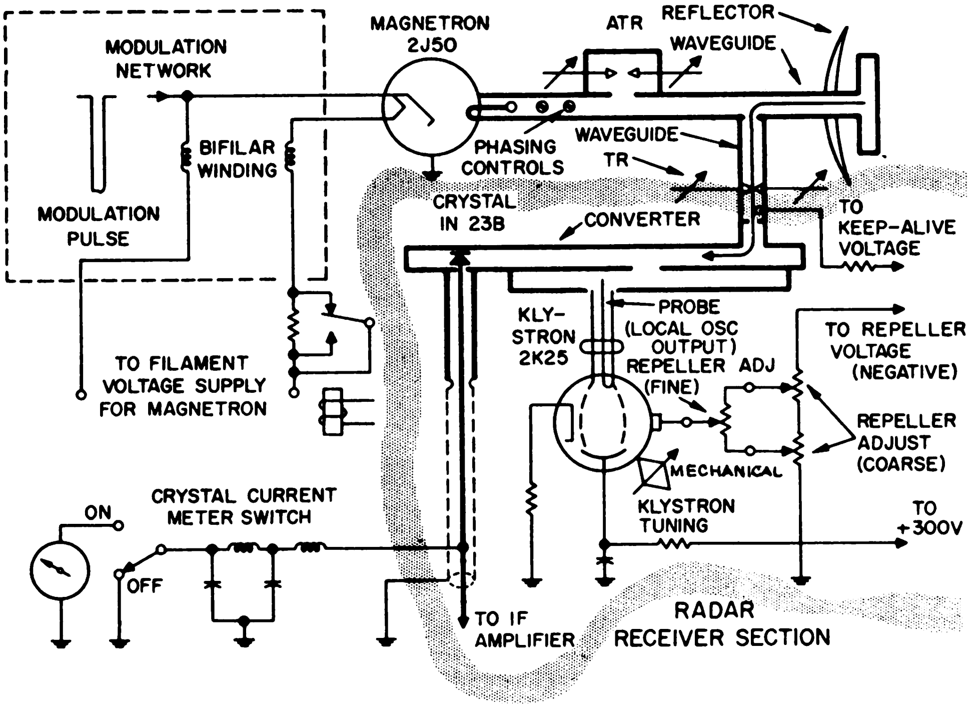


Figure 6-52.—Local oscillator and converter in a radar superheterodyne receiver. 55.116

by adjusting the repeller voltage and adjusting the cavity grid spacing. Its output frequency is fed into the converter section of waveguide by means of a probe. The reflected r-f energy is coupled to the same waveguide section. The 1N23B type crystal is used as the first detector. The output of the crystal is coupled through coaxial cable to the i-f amplifier. The i-f amplifier input is tuned to 60 mc, the difference frequency.

The klystron type local oscillator does not use an ordinary tuned circuit as such; its tuned circuit is built into the tube structure and in physical appearance resembles a cavity enclosed by metal.

Ordinary coils and capacitors cannot be used in tuned circuits at radar frequencies because they would have to be too small to be practical. In addition, the high losses incurred in regular components at these high frequencies would result in an excessively low Q tank circuit. Another important factor to be considered is that leads of ordinary components would be an appreciable portion of a wavelength long. These problems are avoided by using a type of tuned circuit in the klystron that is completely enclosed, as is the case with a resonant cavity.

The two major factors that determine the frequency of oscillation of the klystron are the repeller (negative) voltage and the cavity grid spacing. The repeller voltage is adjusted in the external circuits. The cavity grid spacing is controlled by the mechanical tuning adjustment shown at the lower right of the tube.

Even though the design and construction of fire control radar equipment are very exacting, the frequency of the r-f oscillator, or of the local oscillator, occasionally changes. These frequency changes cause considerable trouble at the radar receiver. A change in either the r-f oscillator or the local oscillator frequency will change the intermediate frequency applied to the i-f amplifiers. The output of the receiver is reduced, and weak target echoes may no longer be visible on the radar indicator. Any change in r-f oscillator frequency, or local oscillator frequency, requires continual readjustment of receiver tuning or the employment of an automatic tuning device. Constant frequency checking by the operator is time consuming and prevents him from accomplishing his other duties when the radar is in operation. Therefore, most fire control radars employ automatic frequency control circuits in which changes in frequency are detected by a discriminator or ratio detector circuit. You learned about these circuits in Basic Electronics, NavPers 10087-A.

The purpose of the discriminator (fig. 6-53) in AFC circuits is to develop a direct current voltage output with a polarity that is determined by the direction of the frequency shift from the intermediate frequency, and that has an amplitude that is determined by the amount of the frequency variation from the intermediate frequency. The discriminator in AFC circuits is a frequency error-detecting circuit. Like other error-detecting circuits, AFC is a form of servosystem. Its output may be zero, some positive voltage, or some negative voltage. No output is an indication of no error. A positive voltage output is an indication of an error in one direction. A negative voltage output is an indication of an error in the opposite direction.

The output of the discriminator is applied as a correction voltage to the automatic frequency control circuits. These circuits in turn develop a correction voltage that is applied to the klystron local oscillator so as to change its frequency by an amount necessary to produce the desired intermediate frequency.

From the block diagram in figure 6-53, you can see that the radar converter has two sections, an AFC section and a receiver section. The local oscillator frequency is fed into both sections. In the AFC section, the local oscillator frequency is mixed with the r-f oscillator frequency to produce the difference frequency—the intermediate frequency. By maintaining the local oscillator frequency at the correct frequency, it is assured that the intermediate frequency will be at the designed intermediate frequency of the receiver.

Most i-f strips have one or more special circuits that compensate for receiver limitations. You have already learned something about one of these special circuits—AFC; but one other special circuit, which comes in several varieties, has not been discussed—gain control.

Gain Control

If you have ever examined your household radio set, you know that it has an automatic volume control (AVC) circuit to keep the output constant over varying levels of carrier power. The radar receiver has one or more circuits that accomplish the same purpose as the radio AVC circuit by varying the gain of the radar receiver with the power level of the input signal.

If a gain-control circuit were perfect, a target would produce an A-scope indication that was the same size regardless of the range of the target. The size of the indication on the scope would depend only on the size of the target. But a perfect gain-control circuit like that just described is impossible because the strength of

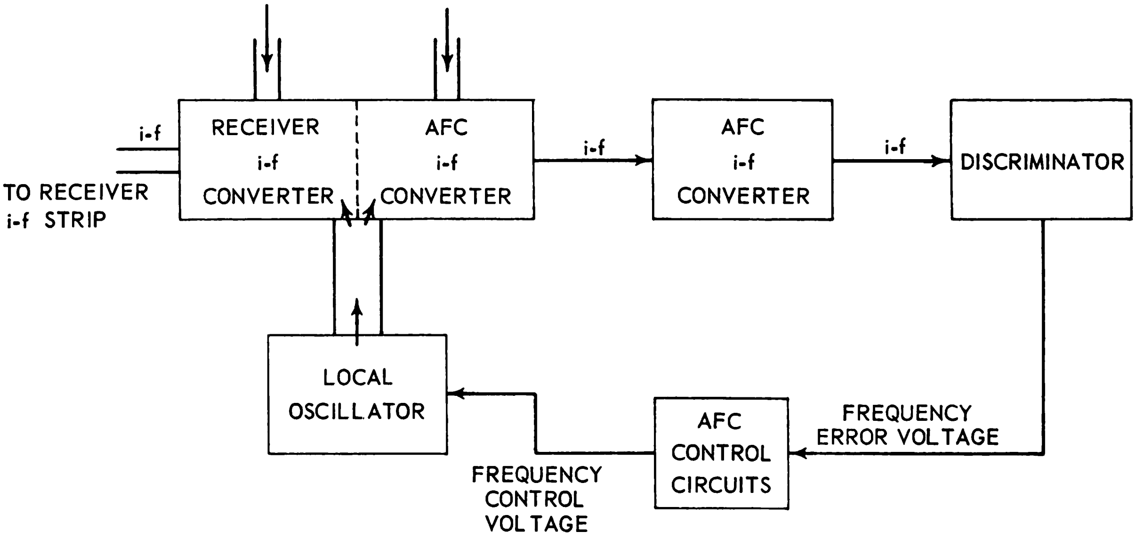


Figure 6-53.—Block diagram of AFC circuit.

55.117

an echo varies inversely as the fourth power of the range. In other words, a target at a 10-mile range produces a signal 10^4 times more powerful than the same target at a 100-mile range. No radar receiver could increase the gain that much in addition to the large gain required to reproduce the signal on the scope. The normal gain of a receiver is so great that it is subject to blocking by large signals. A great increase in gain also lowers the signal-to-noise ratio considerably. Therefore, a form of "inverse" gain control is necessary—that is, instead of increasing the gain for small signals, the gain is reduced for large signals. In this way, the danger of blocking is reduced, and the fundamental purpose of gain control—that of making size in the output—is accomplished to the greatest extent possible.

There are two main types of gain control used in radar sets. The first of these, automatic gain control (AGC), reduces the gain of the receiver whenever a strong signal is received. This prevents blocking of the final stages of the receiver. As blocking is more dangerous in the video stages than in the i-f stages because of the large time constant in the video coupling circuits, AGC circuits are important to the proper operation of the receiver. AGC circuits are also known as instantaneous automatic gain-control (IAGC) circuits.

Another type of gain-control circuit is the sensitivity time-control (STC) circuit. The STC circuit reduces the gain of the receiver immediately after each transmitted pulse and increases the gain with increasing range in an attempt to cause a given target to produce an echo of constant size, regardless of range. STC reduces sea return because the gain is low at short range.

RECEIVER SENSITIVITY

The SENSITIVITY of a radar receiver is its ability to respond to weak echoes. The sensitivity of a radar receiver does not depend on the maximum amount of gain obtainable but on the noise level of the receiver. In other words, the gain could be increased many times above a given figure, but receiver noise would be amplified so greatly that a weak signal could not be seen among the "grass" and "clutter" produced on the indicator scope by the noise. Thus, the noise level of a receiver places a limit on the sensitivity of the receiver. The noise level depends on several factors. The signal-to-noise ratio in the first receiver stage is most important. Increasing the gain increases the noise level as well as the signal level. Receiver gain, therefore, is the result of a compromise between signal amplification and noise amplification.

Increasing the bandwidth of the receiver increases the noise level because noise from a wider frequency range is subject to amplification by the receiver. Yet the bandwidth must be wide enough to accommodate the essential frequencies in the radar pulse. The bandwidth, therefore, is a compromise based on frequency response and noise.

Sensitivity Test

A sensitivity test is one of the most important checks on receiver operation. Although a sensitivity test can be run in several ways, the RINGING-TIME test is one of the simplest and most convenient rough checks of overall equipment performance.

The ringing-time receiver sensitivity test requires only the use of the echo box, which you learned something about earlier in this chapter, and the receiver operating controls. As most modern Navy radars have echo boxes built into the equipment there is little likelihood that you will be without an echo box. For the older radars, specific echo boxes are recommended for use with particular radars.

Table 6-1 shows you how important the sensitivity check is to the effective use of your radar. In a very short time the performance of your receiver can drop so low that you lose more than 50 percent of the range of the radar for small targets. Without regular sensitivity tests, a drop in performance of 15 to 20 decibels passes unnoticed by even the most experienced technician. (Decibels are discussed in Basic Electronics, NavPers 10087-A.) You can see from table 6-1 that a loss of 20 decibels means that the effective range of your radar for aircraft targets is only 31 percent of the effective range for aircraft targets at peak performance. The effective range has dropped to 49 percent of peak performance for periscopes and to 78 percent of peak performance for large ship targets. In other words, if your radar normally detects an aircraft target at a range of 50 miles, a loss of 20 decibels permits the same aircraft to approach within 15.5 miles before being detected. Obviously, such a loss in radar performance exposes your ship to grave danger. Therefore, it is vitally important that you run a sensitivity check at least

Table 6-1.—Effective Ranges of a Radar System for Various Losses in Relative Performance.

Relative performance (decibels)	Effective range for aircraft (percent)	Effective range for periscopes (percent)	Effective range for cruisers (percent)
-1.5	91	94	98
-3	84	88	97
-5	76	82	95
-10	58	69	90
-15	42	58	84
-20	31	49	78
-25	24	40	71
-30	18	34	62
-35	14	28	53
-40	10	24	45
-45	8	20	34
-50	6	16	21

once daily and preferably once during each watch.

The sensitivity of radar may be affected by several factors besides receiver operation. Among these factors are transmitter output power, transmitter frequency spectrum, pulse length, receiver bandwidth, losses in the r-f line, and signal losses in the TR and ATR boxes. However, troubles in the transmitter do not occur nearly so often as troubles in the receiver, and the echo box therefore becomes one of the most important receiver testing devices. Thus, when echo-box tests indicate poor radar performance, the trouble usually lies in the receiver and not in the transmitter.

You will remember that the echo box is a tunable resonant cavity connected to the waveguide by means of a probe and waveguide connector. Some echo boxes also have a small dipole antenna that is connected at a fixed point near the radar antenna. The echo box picks up a small part of the transmitter output energy from the waveguide or from near the antenna and couples this energy into the resonant cavity. An output meter on the echo box indicates when this energy is maximum—that is, when the echo box is tuned to the transmitter frequency. Tuning is controlled by a knurled knob on the echo box, and frequency is indicated on calibrated dials attached to the tuning knob. Most echo boxes have an inner and an outer calibrated dial connected at a ratio of 10:1. The inner dial is the fine-tuning indicator and turns 10 times for every 1 revolution of the outer coarse-tuning indicator. Figure 6-54 shows a dial reading of about 1623.

The procedure for measuring the sensitivity of the receiver with the echo box is as follows:

1. Make sure the cable and couplings from the echo box to the waveguide connector are secure. However, do not change the location of the pickup probe.

2. With the transmitter radiating, turn the tuning dial of the echo box until the echo-box output meter reads maximum. Watching the output meter, turn the dial above and below this

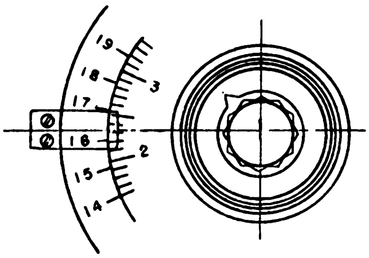
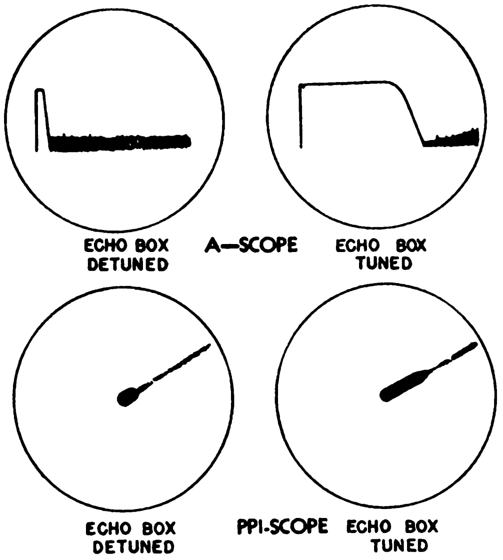


Figure 6-54.—Tuning dial reading an echo box. (The reading is about 1623.) 55.118

maximum until you are sure that you have located the midpoint of the transmitter frequency spectrum. At this point the echo box is tuned to resonance, and a small amount of the energy from the echo box escapes into the waveguide.

3. With the receiver warmed up, observe the indication on the indicator scope. The echo-box signal should appear as a large signal block obscuring a part of the picture. Turn the receiver gain up until the grass is between one-fourth and one-third the height of the signal. If you are using a PPI-scope, turn the gain up until the indicator tube seems to be half covered by flecks of "snow." Figure 6-55 shows indications for both types of indicators when the echo box is detuned and tuned.



55.119

Figure 6-55.—Indications on A-scopes and PPI-scopes when the echo box is detuned and tuned.

4. You can now measure the ringing time of your receiver. Ringing time on an A-scope is the distance in yards from the leading edge of the echo-box signal block to the point where the grass reaches normal height at the trailing edge of the signal block. As you can see in figure 6-56, ringing time is NOT measured across the top of the signal block, nor is it measured to the point where the trailing edge of the signal block strikes the base line of the sweep.

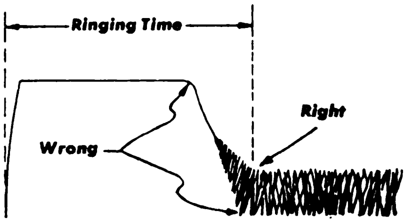


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Figure 6-56.—Correct and incorrect way of measuring ringing time on an A-scope.

On a PPI-scope the ringing time is measured from the center of the scope to the faintest outer edge of the signal block. Figure 6-57 shows the ringing time for a PPI-scope with echo boxes using both a directional coupler and a fixed dipole input.

To assure an accurate reading, this test should be run about four times in succession, and an average of the four readings should be taken. The transmitter varies slightly in frequency from time to time, but when an average of four readings is taken all frequency variations tends to cancel one another. The average reading should be compared with the optimum reading for the radar given in the OP and with the previous daily readings for the radar.

The OP for the radar (for built-in echo boxes) or the OP for the echo box (for separate echo boxes) interprets a loss in yards in terms of a loss in decibels of receiver sensitivity. On the average, a loss of about 80 yards of ringing time means a loss of about 1 decibel in receiver performance. By referring to table 6-1, you can see approximately what this means in loss of effective range of the radar.

When you have completed the test, always detune the echo box so that it does not interfere with normal reception. The echo box is detuned by turning the tuning dial as far as possible from the maximum indication on the output meter.

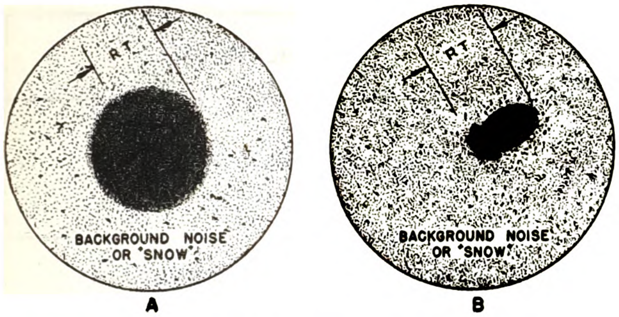


Figure 6-57.—Correct way to measure ringing time on a PPI-scope. 55.121

In measuring ringing time, the operator should make sure that he is tuning on the echo-box indication and not on some other large block of signals from a nearby land mass. If the ringing-time indication moves back and forth as the gain control is changed, the signal on the scope is from the echo box. If the signal merely changes in amplitude but not in range, then the receiver is tuned on some other large block of signals.

Factors Affecting Sensitivity Readings

An echo-box sensitivity reading may appear to be normal and yet be incorrect. This may result from several troubles: (1) the receiver bandwidth may be narrowed because of an oscillating i-f stage, (2) the transmitter may be off-frequency or firing erratically, and (3) the radar pulse may be too long. Let's look at these troubles more carefully and see whether they can be detected and prevented.

The receiver bandwidth may be decreased by an oscillating i-f stage. Oscillation can be recognized by a coarseness of the grass and by a tendency of the gain to increase sharply at a particular setting of the gain control.

If the transmitter is off-frequency or firing erratically, less power may be sent in a wider pulse. The echo box gets less power than before, and the output meter reading is low. The ringing time usually is slightly lower than normal in this case. When you suspect the existence of a situation like that just described, run a spectrum analysis on the transmitter pulse.

If the ringing time fluctuates erratically but the output meter reading is normal and steady, (1) the radar may be pulsing at half its normal rate, (2) the pulse spectrum may be wide and erratic, or (3) the echo box may be slightly detuned. Echo-box detuning, of course, is easy enough to check by tuning the echo box. Faulty pulsing or an abnormally wide pulse usually shows up in a spectrum analysis of the radar pulse.

If both output meter and ringing time are erratic, you have poor connections to the echo box or a bad r-f line. Tapping the suspected line should produce synchronous fluctuations of the meter and the ringing-time indication.

Figure 6-58 shows ringing-time indications on an A-scope and typical output meter indications on the echo box for different radar troubles. This figure should be helpful to you in evaluating the trouble when you get a poor echo-box test.

MEASURING RECOVERY TIME

If your receiver has poor recovery time, the echo box shows it as a lack of normal grass immediately following the ringing-time indication. The upper right-hand illustration in figure 6-55 shows this condition. In receivers with poor recovery time the grass usually increases gradually in intensity until it appears normal toward the end of the scope, but occasionally it fails to show up altogether. Poor receiver recovery time indicates a weak or defective i-f or video stage.

The recovery time of the TR tubes also can be tested with the echo box. Figure 6-59 shows the proper way to measure TR recovery time. The gain control of the receiver is lowered until there is a smooth drop in the ringing time, as shown by curve D in figure 6-59. Curve D differs markedly from receiver saturation, shown in curve E. The recovery time is measured from the leading edge of the ringing-time pattern to the point where a sharp drop in the trailing slope of the pattern is seen. The radar OP gives the proper recovery time; it should be less than 1 mile. If your reading is greater than the proper value, you must replace the TR tubes and retune them if this is required. A TR tube that is completely defective produces a ringing-time pattern like that shown in H of figure 6-58.

RECEIVER ALIGNMENT

The radar receiver has been aligned carefully at the factory and should not need further aligning. Aligning a broad-band receiver with

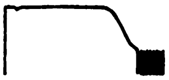
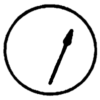
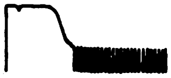
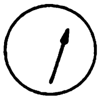
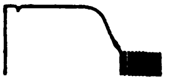
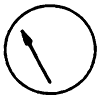
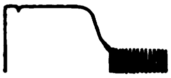
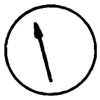
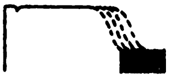
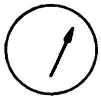
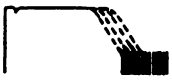
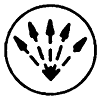
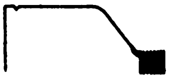
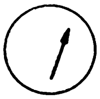
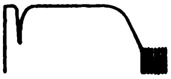
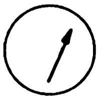
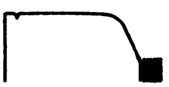
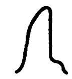
EFFECT	APPEARANCE ON		PROBABLE CAUSE
	RADAR INDICATOR	ECHO BOX METER	
RINGTIME — NORMAL ECHO BOX METER — NORMAL			RADAR PERFORMANCE SATISFACTORY.
RINGTIME — LOW ECHO BOX METER — NORMAL			RECEIVING TROUBLE: DETUNED MIXER OR LOCAL OSCILLATOR, BAD CRYSTALS, EXCESSIVE I-F NOISE, ADJUSTMENT OF PROBES IN MIXER CAVITY, DETUNED T/R BOX.
RINGTIME — LOW ECHO BOX METER — VERY LOW			LOW POWER OUTPUT-CHECK SPECTRUM.
RINGTIME — LOW ECHO BOX METER — LOW			TROUBLE PROBABLY IN TRANSMITTER AND RECEIVER AND/OR TROUBLE IN TRANSMISSION LINE.
RINGTIME — ERRATIC ECHO BOX METER — STEADY			ECHO BOX DETUNED. BAD PULSING, DOUBLE MODING TRANSMITTER, OR LOCAL OSCILLATOR POWER SUPPLY TROUBLE. CHECK SPECTRUM.
RINGTIME — ERRATIC ECHO BOX METER — ERRATIC			FAULTY TRANSMISSION LINE OR CONNECTION — CONDITION WORSE WHEN LINE IS VIBRATED.
END OF RINGTIME SLOPES GRADUALLY, POSSIBLY EXCESSIVE RINGING. GRASS APPEARS COARSE. ECHO BOX METER-STEADY AND SATISFACTORY.			OSCILLATING I-F STAGE
PRONOUNCED DIP IN RINGTIME AT END OF PULSE.			FAULTY T/R TUBE
RINGTIME-SLIGHTLY LOW POOR OR BAD SPECTRUM.		 POOR SPECTRUM	TRANSMITTING TROUBLE

Figure 6-58.—Echo box troubleshooting chart.

55.122

a number of tuned stages is a tough job. It requires special equipment and a technician skilled in test equipment use. As a result of the difficulty in aligning the i-f strip, most fire control radars have replaceable i-f strips. The entire defective strip may be taken out of the receiver and a new pretuned strip put in its place. The old strip may be returned to the factory.

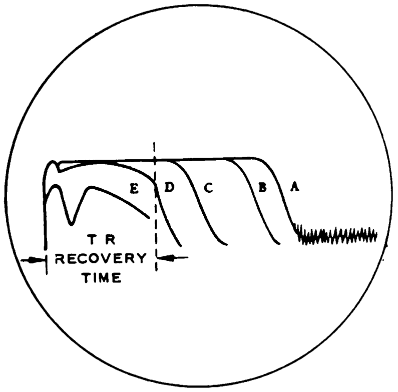


Figure 6-59.—Proper way to measure TR box recovery time. 55.123

RECEIVER TROUBLESHOOTING

Most radar troubles occur in the receiver. Therefore, if you have isolated a trouble to two or three possible units, one of which is the receiver, always begin your search in the receiver. Let's examine a few possible causes of receiver trouble in the order of their likelihood.

Tube Failure

In the receiver, as in most other units of the radar, the most likely cause of trouble is tube failure. This fact is complicated further by the fact that even a slight change in the operating characteristics of a tube because of age, temperature, or vibration can result in poor receiver operation. A tube may check "good" on the tube tester and still be defective so far as proper operation of the receiver is concerned. Therefore, all tube check must be by replacement of spare tubes that have been checked previously in the equipment.

The tubes that are most vital to proper receiver operation are in the first i-f stages. Therefore, if you must use weak or aging tubes in the i-f strip, place them in the final stages, where they least affect operation of the receiver.

Crystal Failure

If the receiver appears to be operating normally, but the scope shows only "grass" and either no signals or weak signals, the crystal mixer is among the first things to check. The crystal mixer—either the signal mixer or the AFC mixer—can be defective without reducing the reading of the crystal current meter to any significant degree. The crystal current meter can indicate an "open" crystal but not a poor crystal; so the only sure way to find whether the crystal is defective is to substitute a new one. You should try two or three new crystals before deciding that the crystal is not the source of trouble, because sometimes there are defects or variations in sensitivity in new crystals.

The crystal is in a cartridge holder, and usually is located in the r-f line near the TR box. With the equipment off, unscrew the retaining cap, pull the old crystal, and insert the new one. Ground your finger on the crystal holder before inserting the new crystal, because the static charge on your body may be enough to destroy the crystal.

Local-Oscillator Tuning

When you install a new local oscillator, or when tests show the old local oscillator to be detuned, you must tune the local oscillator to give the proper intermediate frequency.

With reflex klystron local oscillators, the fastest method of tuning is by use of the echo box. With the transmitter on, tune the echo box for a maximum reading on its output meter. Shut off the receiver AFC and use manual tuning. During the test, keep the crystal current meter below 0.6 milliampere by adjusting the signal crystal current adjustment screw. Turn the local-oscillator tuning control to zero, then increase the frequency until the echo-box reading appears to be maximum on the scope. If the local-oscillator tuning control is turned farther, the scope reading disappears and then reappears. The first maximum scope reading occurs when the local oscillator is tuned above the magnetron frequency by the intermediate frequency. The second maximum scope reading occurs when the local oscillator is tuned below the magnetron frequency by the intermediate frequency. If the AFC operates above the magnetron frequency, tune on the first maximum reading; if the AFC operates below the magnetron frequency, tune on the second maximum.

Finally, adjust the coupling screw on the signal crystal to give the proper reading on the crystal current meter. With most radars the proper reading is about 0.5 milliampere. The radar OP gives complete instructions for tuning the local oscillator, and also gives the correct reading for the crystal current meter.

AFC Tuning

If you have reason to suspect that the automatic frequency control is locking in at the wrong intermediate frequency and hence is reducing the output of the receiver, you can check the lock-in frequency with the echo box. With the automatic frequency control on, tune the echo box for maximum receiver ringing time and record your reading. Then with the automatic frequency control off, adjust the local-oscillator tune control for maximum receiver ringing time. The two readings should be exactly the same. If the first reading is even slightly less than the second, you must adjust the tuning coil in the discriminator to produce zero output on the correct intermediate frequency.

Oscillation

High-gain amplifiers have a tendency to oscillate because of regenerative feedback. Oscillation is guarded against in most receivers by decoupling filters in the plate and heater leads to the i-f amplifiers. The filters are made resonant at the intermediate frequency so that they present a high impedance between stages.

Failure of the bypass capacitors in either the plate leads or the heater leads allows oscillation to occur. Oscillation shows up as an erratic pattern and as reduced sensitivity on the radarscope. The gain has a tendency to change sharply when the gain control reaches a certain setting.

One way to find out which stage is oscillating is to remove the tubes in the i-f stages one at a time and to place a small (50 - 100 micro-microfarad) capacitor across the stage. You can do this without removing the receiver from the radar cabinet. Merely insert the capacitor leads in the grid and plate sockets of the stage. If it is the oscillating stage, the scope picture will become stable. The gain may even increase, because oscillation of one stage decreases the signal to the following stages.

In an emergency you can operate the receiver with a capacitor shunting out one i-f stage, particularly if it is not the first or second stage. You can increase the gain control to compensate somewhat for the missing stage, but as soon as possible you should locate the real trouble and correct it.

The foregoing procedure does not work for the video stages because the phase shift introduced by the capacitor causes a defective scope reading. You should use the capacitor only when you cannot correct the oscillations by replacing tubes in the i-f strip.

Overall Procedures

When testing the receiver to locate a trouble, you can determine whether the trouble is in any one of the special circuits—AGC, STC, or FTC—by observing the operation of the receiver first with the special circuits operating and then by observing whether the trouble disappears when the special circuits are turned off. After testing each special circuit in this way and finding it to be operative, turn off all the special circuits and check the main i-f and video stages. In most radars, you can determine whether the trouble is in the final video stages by observing the monitor scope. If the trouble is not on the monitor scope but on the main scope or repeater scope you can isolate the trouble to the final video stages because most monitor scopes operate from the output of the first video stage. If the trouble appears on all the scopes, then the difficulty must be in the stages preceding the final video stages—the input, the mixer, the local oscillator, the i-f stages, the detector, or the first video amplifier.

Most radars have test jacks for each i-f stage and for numerous other trouble spots. From the radar OP you can find out the location of the factor that should be tested at each jack and the correct readings that should appear. In the OP you can find troubleshooting charts, which should help you in systematically locating a trouble without waste of motion or time. Unless you are positive that you know what the trouble is and how it can be corrected, don't attempt to service any part of the radar without the help of the OP.

INDICATORS

The video-frequency signal from the output of the radar receiver is fed to the indicator unit. The indicator unit consists of an indicator scope and the electronic circuits that are necessary to present the desired information on the scope. In this discussion we shall consider only the methods of presenting the desired information on the radarscope, and the external operating controls for the radar indicator scope. The electronic circuits required to operate the scope are considered in detail in Basic Electronics, NavPers 10087-A.

COMPARISON WITH OSCILLOSCOPE

The type of scope used by most radars is similar to the type used in fast-sweep test oscilloscopes. The radarscope uses a rapid linear sweep with time intervals in microseconds.

All cathode-ray tubes have a few common elements. There is an electron gun, or cathode, that produces a beam of electrons. The face of the tube is covered on the inside surface with a phosphor coating that emits light when excited by the electron beam. The walls of the tube are coated with a conducting material that is kept at a high potential with respect to the cathode. This conducting material acts as an anode and collects the electrons after they have excited the phosphor coating on the face of the scope. Most cathode-ray tubes have one or more grids, as well, to regulate the electron beam in direction and intensity.

METHODS OF DEFLECTION

The basic difference between cathode-ray tubes lies in the method by which the electron beam is deflected, or moved, across the face of the tube. There are two widely used methods of deflecting the electron beam. One is known as ELECTROSTATIC deflection and the other as ELECTROMAGNETIC deflection.

Electrostatic Deflection

The simpler method is electrostatic deflection. Four plates—two horizontal and two vertical—are in the tube. Each plate is an equal distance from the center path of the electron beam. (See figure 6-60A.) In an electrostatic tube using type-A scan, the sweep is caused by applying a linear sawtooth voltage to the vertical (horizontal-deflecting) plates. As the electric field between these plates is increased linearly, the electron beam is deflected across the face of the tube in a horizontal sweep. Incoming signals are applied to the horizontal (vertical-deflecting) plates, where they cause the beam to deflect up or down on the face of the tube. The electrostatic cathode-ray tube is focused by changing the potential on the first anode in the neck of the tube. Most tubes of this type are used in type-A scopes and provide a range-only indication. Some tubes of this type are used for B-scope presentation, although the sweeps are not generated quite like those just described for the A-scan. Electrostatic scopes are used extensively in oscilloscopes and small indicator scopes. However, the larger the face of the tube, the greater must be the deflecting voltage on the deflection plates; hence, electrostatic scopes that are more than 7 inches in diameter are rare.

Electromagnetic Deflection

In an electromagnetic cathode-ray tube, two coils just outside the tube are substituted for the deflecting plates of the electrostatic tube. A magnetic field, and not an electric field, causes the sweep in this tube. Remember that the strength of a magnetic field varies directly with the current in the coil. Thus the current, rather than the voltage, must be a linear sawtooth wave in order to produce the sweep in an electromagnetic tube. (See figure 6-60B.)

The electron gun in a cathode-ray tube requires some system to focus the electron stream into a beam. This is done either electrostatically by means of electrodes inside the tube, or magnetically by means of an external electromagnet or permanent magnet.

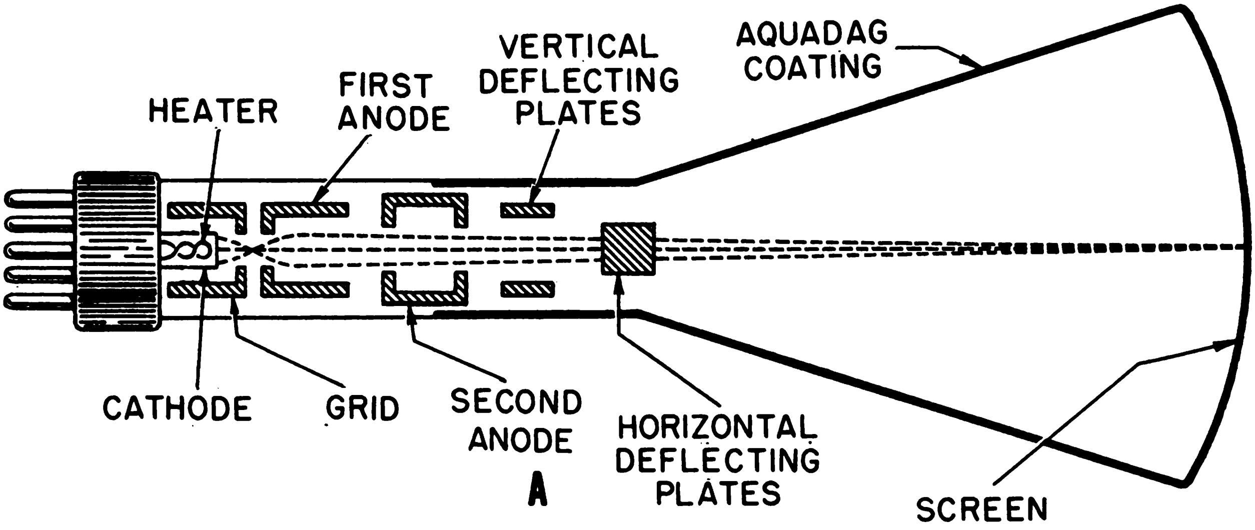
METHODS OF DISPLAYING INFORMATION

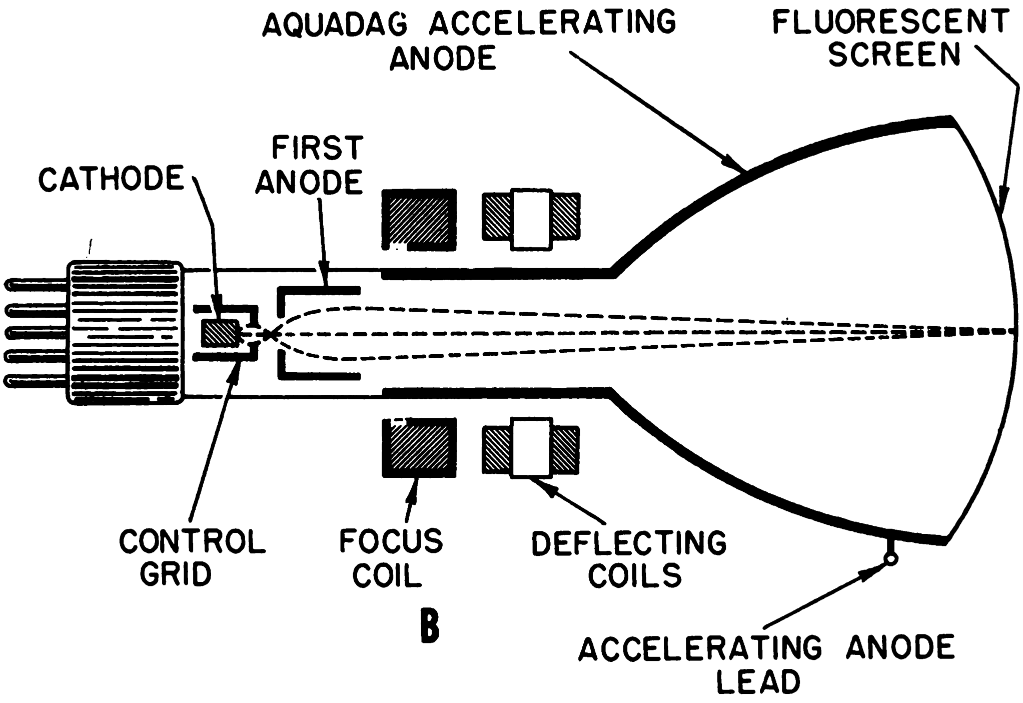
There are many methods of visually presenting the information obtained by a radar. The method used depends on (1) the type of information to be presented, (2) the use to which the information is to be put, and (3) the type of radar.

Four of the most common types are discussed here. These are (1) the A-scope, (2) the A/R-scope, (3) the B-scope, and (4) the E-scope.

A-Scope Presentation

In A-scope presentation the x, or horizontal, axis represents range, and the y, or vertical, axis represents signal amplitude. The latter is indirectly used to obtain bearing, because signal amplitude is greatest when the antenna is pointing directly at the target. Figure 6-61 shows an A-scope presentation. The type-A scope, as you can see, displays echo amplitude against a time base which is calibrated to represent





A. Electrostatic
B. Electromagnetic
Figure 6-60.—Cathode-ray tubes.

20.320(55)

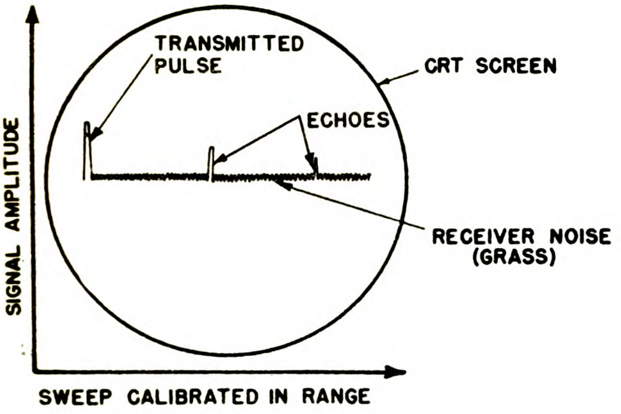


Figure 6-61.—A-scope presentation. 55.124

range. This presentation's usefulness is limited to showing slant range directly.

A/R-Scope Presentation

Because the A-scope is unable to measure the target's range with a high degree of accuracy, it is necessary to develop a means of so doing. The A/R scope, shown in figure 6-62, provides a double-trace presentation. The lower trace (A-sweep) is similar to the A-scope presentation. A notch in the A-sweep, called a range mark, is movable and can be set on the target pip by the operator. The upper trace (R-sweep) is an expansion of that portion of the A-sweep representing several hundred yards either side of the range mark. Thus by adjusting the position of the range mark, the operator can examine any desired portion of the A-sweep on the expanded R-sweep. By adjusting the range mark's position the target pip can be brought exactly to the edge of the range step, which is simply a drop in the level of the R-sweep fixed at the center of the scope. Range can thus be very accurately measured on the calibrated control knobs.

B-Scope Presentation

In the B-scope presentation the picture seen is that of a narrow, wedge-shaped segment of space. Whenever the radar equipment picks up a target a bright spot appears on the scope in a position corresponding to the position of the target. The centerline or zero bearing line is aligned with the line of sight of the director. The distance between vertical lines represents intervals of about 3 degrees in bearing. Ranges are measured upward from the bottom of the scope by shifting the horizontal range line until it touches the bottom of the echo and reading the range on a calibrated dial. The exact bearing of a single target is obtained by training the director until the zero bearing line bisects the target, as shown in figure 6-63.

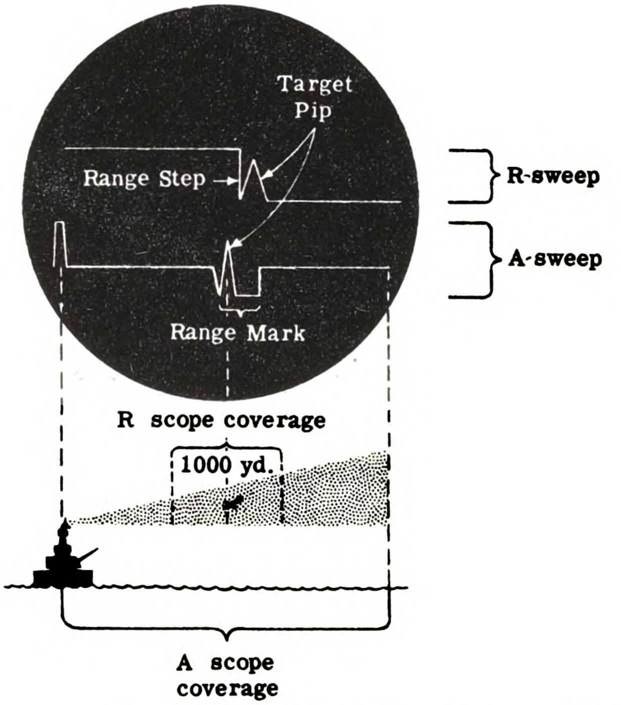


Figure 6-62.—The A/R-scope. 55.125

E-Scope Presentation

The type E-scope, shown in figure 6-64, is similar to the B-scope, except that it presents range horizontally and target elevation on the vertical scale. The target echo appears as a short vertical pip. The coverage or sweep of the radar beam is represented by a series of horizontal traces across the scope face between the elevation angles scanned by the radar beam. A vertical range mark is used in the same manner as the B-scope range line to measure range. Two curved lines on the scope face furnish an indication of target altitude. No measurement of target bearing is possible with this scope; it must therefore be obtained from a separate indicator such as a B-scope.

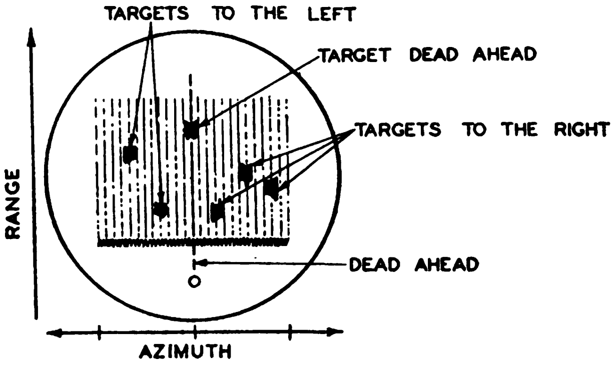


Figure 6-63.—B-scope presentation. 55.126

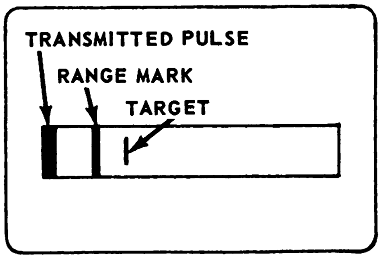


Figure 6-64.—Type E-scope. 55.127

INDICATOR TROUBLESHOOTING

Troubles in the indicator are relatively easy to detect because the indicator tube itself acts as a cathode-ray oscilloscope. When troubles occur in the indicator, they usually can .be diagnosed by the appearance of the indication.

For purposes of location and correction, indicator troubles can be divided into two types. One type of trouble affects the video circuit. This trouble generally appears as an absence or distortion of the signals on the radarscope. The other type of trouble affects the trigger-operated circuits. This trouble usually appears as an absence or distortion of the sweep or range marks on the radarscope.

Video Troubles

After isolating a trouble to the video circuits, you should decide from the appearance of the trouble on the scope (if there is a video indication on the scope) what the most probable cause of the trouble is. If there is no video indication on the scope, check the video inputs from the receiver with an oscilloscope. Jacks are provided for this purpose. If the receiver provides a video output and if the connecting cable is intact and secure, then you know that the trouble must be in the indicator video channel.

As with most radar units, tubes are a likely cause of trouble. Thus, unless the scope indicates some other cause as being more likely, you can start your check by replacing the tubes in the video channel and seeing whether the trouble is corrected. If the trouble still exists, you must check the output of each of the video stages with a test oscilloscope. When you locate the place where the signal disappears or becomes distorted, check the voltages and resistances at the base of the stage until you find the point at which the readings differ greatly from those given in the OP. You can probably locate the trouble at this point. It may be a short circuit, a loose connection, a poor resistor, or a bad capacitor.

Trigger-Circuit Troubles

If the trouble is isolated to the trigger-operated circuits—that is, to the sweep circuits, the range-mark circuits, and so forth—it generally is more difficult to locate. The best procedure to follow is somewhat like that for the video circuits. First, check to see whether, from the appearance of the scope picture, you can isolate the trouble to any one particular channel. Try to find out whether the sweep circuits or the range-mark circuits are causing the trouble. If the indications from both sweep and range-mark circuits are absent, check the trigger input from the timer. Do this by connecting a test oscilloscope to the trigger input jack.

If the triggers are not present, you probably can find the trouble in the synchronizer; if the triggers are present, you must begin a stage-by-stage check of the indicator trigger-operated circuits. Here again, you should attempt to locate the trouble first by substituting tubes from the set of spares that have been tested in the equipment. If you cannot locate the trouble in this way, use a test oscilloscope to try to find the stage at which the trigger disappears or becomes distorted. After locating the faulty stage, you can begin checking voltages and resistances to see whether they agree with the proper readings given in the OP.

SUMMARY

As you know, a fire control radar is a complex system containing intricate circuitry and mechanical components. Although the materials and workmanship used in their manufacture are the best obtainable, electronic parts and mechanical devices often become inoperative. Thus, to ensure reliability, it is imperative that radar sets be tested periodically.

When you make a test of your radar, don't rely on visual observation alone to determine if it is operating properly. Reliance on visual operation as a judge of range capability and data accuracy of radar systems has been found to be so inaccurate as to be completely worthless. For example, one day you may be able to pick up targets at maximum range. The next day you may not be able to detect targets at half the range capability of your set. The reason for this is that your set may not be putting out maximum power. The first day you may have had a thermal duct working in your favor. You can see from this simple illustration that a power output check would have shown that your radar was not working at its designed efficiency. Another case in point is tracking sea gulls to determine radar performance. This test has some merit; however, it mostly indicates the ability of a radar system to track sea gulls and should not be used as a performance standard.

This chapter is an effort to help you learn the basic principles of radar testing. The treatment is general enough to cover some testing phase in all types of fire control radar. Specific and special testing information on a particular radar is found in its OP and/or its POMSEE series of publications. Another excellent source of information is the Handbook of Test Methods and Practices, NavShips 91828.

CHAPTER 7

TARGET POSITION AND RELATIVE MOTION

The fire control problem is included in this course to give you a foundation for understanding your fire control system. A statement of the fundamental fire control problem is presented in the Navy Training Course, Fire Control Technician 3, NavPers 10173-A. A thorough knowledge of this statement is necessary to understand the problem's solution.

TARGET'S PRESENT POSITION

A target's position can only be described by relating it to a known reference point, for position is a relative quantity. We describe a location by measuring its direction and distance from a point known to us. (Try to describe any location, say the director or plotting room, without a known starting or reference point.)

The need for a reference or starting point to describe target's position is obvious. It can also be seen that a system of measuring direction and distance from that reference point is needed. The reference point is contained in a frame of reference. The systems of measuring from the reference point are called "coordinate" systems.

FRAME OF REFERENCE

A frame of reference is a system of lines, angles, and planes within which we can measure a target's present position. Each frame of reference has a point from which all measurements are made. This point is called the reference point or the origin. A baseball field can serve to show what we mean by frame of reference. The playing field is established from home plate by the foul lines. The game takes place within these lines. All measurements are made from home plate, the reference point. The importance of the location of the reference point is apparent, since everything is related to it.

There are four frames of reference used in naval fire control. Each is determined by the method used to establish the reference point. The reference point is normally located within own ship or the destructive package. (Examples of the term "destructive package" as used here are missile and torpedo.) The advantage in this location is that all measurements are therefore made with respect to own ship or the destructive package.

The four frames of reference are coordinate systems rigidly attached to (1) own ship, (2) the earth, (3) the destructive package, or (4) inertial space. A fire control system may use any one of these frames, or possibly a combination of them. The frame being used can be recognized by the reference point's location and how it was established.

The frame of reference, RIGIDLY ATTACHED TO OWN SHIP, has a reference point which is built into the weapon system. The system is unstabilized. All measurements of target's present position are made from the reference point located in the deck plane. The deck plane moves in all directions with own ship. The GFCS Mk 63, for example, uses this frame of reference.

The EARTH frame of reference is considered attached to the surface of the earth and rotates with the earth. The reference point is contained in the horizontal plane, which is independent of ship's roll and pitch. The horizontal plane is established by a gravity-seeking device (stable element) within own ship or the destructive package. The fire control systems using this frame of reference can be either fully or partially stabilized.

In a system fully stabilized all measurements of the target's position are made with respect to the horizontal and vertical planes. In a partially stabilized system only a section of the system is stabilized. The stabilized section, normally the computer, measures target's position with respect to the horizontal and vertical planes.

In the other sections of the weapon system (director, weapon launcher) the reference point, located in the deck plane, moves with the ship in all directions. The GFCS Mk 37 and main battery systems are examples which use this frame of reference.

The earth frame can be considered inertial for short times of flight, since the error caused by earth's rotation is so small it can be ignored.

The frame of reference, RIGIDLY ATTACHED TO THE DESTRUCTIVE PACKAGE, has a reference point built into, and moving with, the destructive package. The destructive package's reference planes containing the reference point are orientated to own ship's reference planes when the source of guidance is located in own ship. When the source of guidance is contained in the destructive package, its reference planes are oriented to the earth or to an inertial space frame. Missile and torpedo systems, for example, may use this frame of reference.

The INERTIAL SPACE frame of reference is considered independent of earth's motion and to have a constant velocity with respect to a "fixed star"—for example, Polaris. The reference point is considered to be at the center of the earth and therefore nonrotating. This reference point can be established aboard ship or in the destructive package if an inertial device (such as a free gyro) is used. The inertial space reference is used when the time of flight is long and the effects of earth's rotation must be considered.

COORDINATE SYSTEMS

The target's present position is located in a frame of reference by a coordinate system. The coordinate system measures the target's distance and direction from the reference point. A coordinate system gives a graphic representation of the target's present position.

We can define a coordinate here as a number representing the length of a line that has a known direction relative to a reference axis. To locate a point in a plane requires two coordinates. Each coordinate represents a dimension. As an example, own ship's location can be determined by the coordinates of latitude and longitude (fig. 7-1). It would follow then that a surface target's location from own ship can be determined by two dimensions. In this case both own ship and the target are in the same plane.

There are two basic coordinate systems used to locate a point in a plane: (1) the rectangular or Cartesian coordinate system, which uses two linear coordinates; and (2) the polar coordinate system which uses one angular and one linear coordinate.

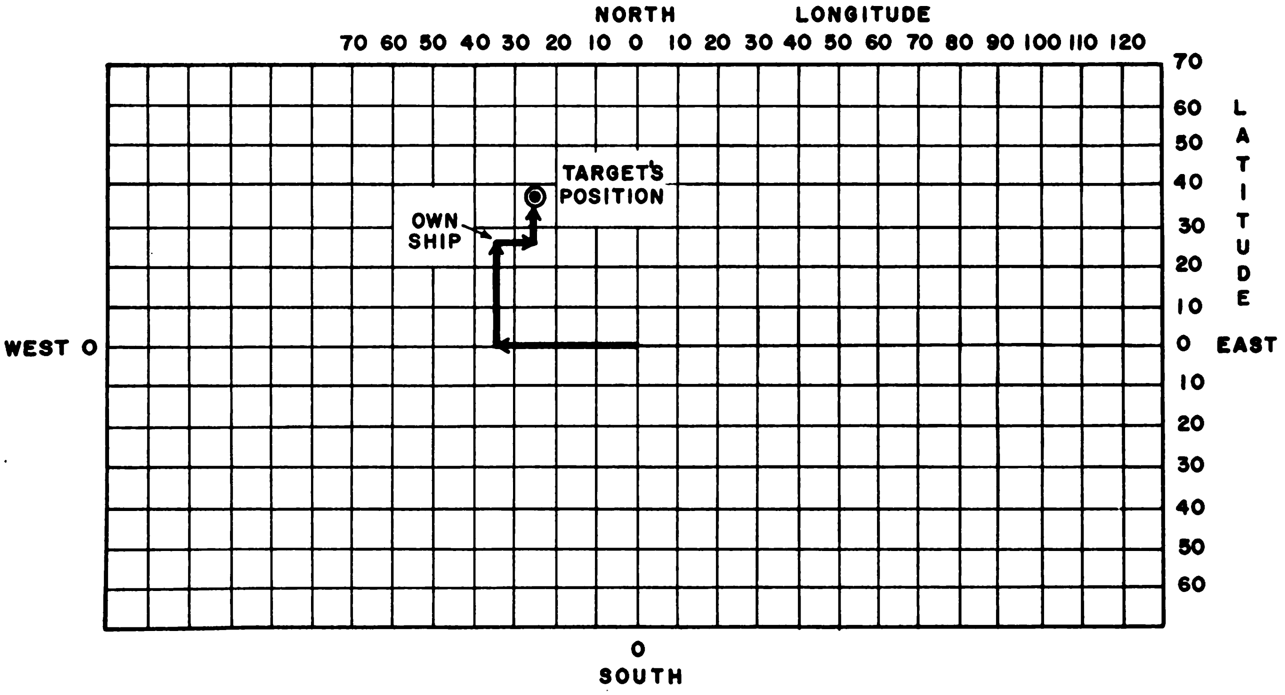
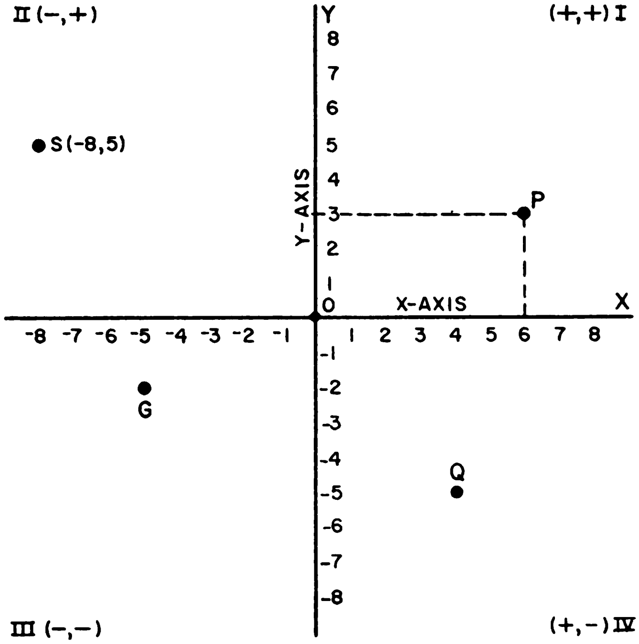


Figure 7-1.—Earth's coordinates (latitude-longitude).

55.128

Rectangular Coordinate System

The rectangular coordinate system uses a frame of reference similar to that shown in figure 7-2. The two lines, X and Y, intersect at right angles. The horizontal line is usually labeled X and called the X axis. The vertical line is usually labeled Y and called the Y axis. The point where the X and Y axes intersect is called the origin, and is labeled with the letter O. The origin is, of course, our old friend, the reference point.



55.129

Figure 7-2.—Rectangular coordinate system.

The origin is the starting point for measuring along both axes. To the right of the origin, numbers on the X axis are positive and to the left they are negative. The numbers along the Y axis above the origin are positive; below the origin they are negative.

A point anywhere in the plane of the graph may be located by two numbers. One number shows the distance of the point from the origin along the X axis. The other number shows the distance of the point from the origin along the Y axis. Thus, point P in figure 7-2 is 6 units to the right of the origin along the X axis and 3 units above the origin along the Y axis. When we write the coordinates, the X coordinate is always written first. The coordinates for point P would be written: P(6, 3).

QUADRANTS.—The X and Y axis divide the graph into four parts called quadrants. In figure 7-2, point P is in the first quadrant; point S is in the second quadrant; point G is in the third quadrant; and point Q is in the fourth quadrant. In the first and fourth quadrants, the X coordinate positive, because it is to the right of the origin. In the second and third quadrants, the X coordinate is negative, because it is to the left of the origin. The Y coordinate is positive in the first and second quadrants, being above the origin, and negative in the third and fourth quadrants, being below the origin. The signs of the coordinates in the quadrants are shown in the figure.

Locating points with respect to axes is called "plotting the points." As shown with point P (fig. 7-2), plotting a point is equivalent to completing a rectangle. This is the reason for the name rectangular coordinate system.

Polar Coordinate System

The polar coordinate system is developed on a frame of reference similar to the rectangular coordinate system. The two lines, X and Y (fig. 7-3) interesect at right angles. The origin, labeled with the letter O, is at the point of intersection. The origin is the axis, or pole, around which the angular coordinate revolves.

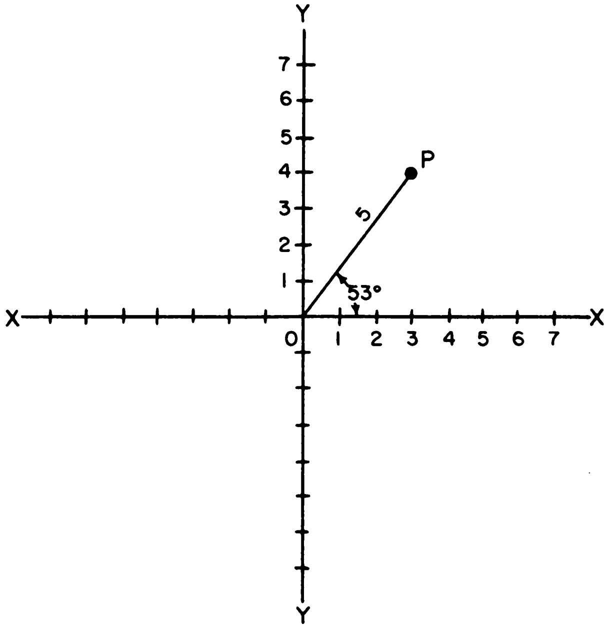


Figure 7-3.—Polar coordinate system. 55.130

A point anywhere in the plane of the graph can be located with two coordinates. The linear coordinate is the distance of the point from the origin. This distance is called the radius and is usually symbolized by the letter r. Since r denotes distance (range) and not direction, it is always positive.

The angular coordinate is measured from the X axis to the right of the origin. The angle increases as it is rotated counterclockwise. In fire control, we know that the angle (bearing) is measured from the Y axis. Also the angle increases as it is rotated in a clockwise direction. This is done for convenience, and, conventionally, bearing is measured clockwise. The principles of the polar coordinate system remain the same. We simply have reversed the direction of rotation and shifted the axis 90 degrees.

In describing the location of a point, the coordinates are placed within parentheses. The linear value is always written first. The coordinates of point P (fig. 7-3) are written: P(5, 53°). Thus, point P is five units from the origin along a line that forms an angle of 53° with the X axis.

Three-Dimensional Coordinate System

Until now we have assumed the target would be in the same plane as own ship. If a target is not on the surface of the earth, three dimensions are required to describe its position. We already know about tri-dimensional measurements—length, width, and depth.

To locate a point not in the reference plane, the point's deviation from the reference plane must be described. The deviation is its height measured from the reference plane. The deviation can be described by either an angular (elevation) or linear (altitude) value.

When the angle of elevation is used (fig. 7-4), the angle is measured at the origin. One side of the elevation angle is in the reference plane. The other side, the line R, connecting the origin with the target, is in a slant plane.

The line, Rv, establishes point P in the reference plane. Rv is constructed perpendicular to the reference plane; thus point P is directly beneath the target. The polar coordinate, Rh, and the bearing angle, ϕ , describe the position of point P in the reference plane. The third coordinate, describing target's position with respect to the reference plane, is the measured angle of target's elevation.

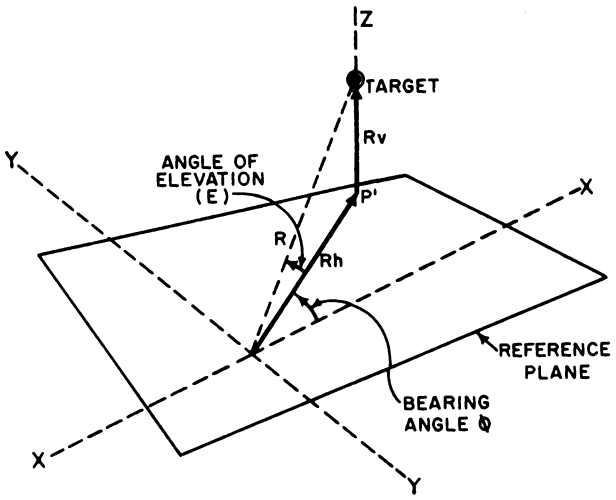


Figure 7-4.—Three-dimensional polar coordinate system.

55.131

The linear value of target's altitude, Rv, can be computed from the right triangle (R, Rh, Rv) in figure 7-4. The distance (R) of the target from the origin and the angle of elevation are measured. The linear value of Rv can be found by the formula

$$Rv = \sin E \times R$$

The distance from the origin of point P in the reference plane can be found by the formula

$$Rh = \cos E \times R$$

The position of the target in figure 7-5 can be described by three coordinates. We first establish point P in the reference plane, directly beneath the target. The position of point P can be described by the rectangular coordinate (Rhx, Rhy). The altitude, Rv, is the third coordinate used to describe target's position. The altitude is measured along an axis perpendicular to the reference plane. This axis is usually labeled with the letter Z, and called the Z axis.

Transmission of Coordinates

Normally targets are detected by the ship's search radar. Target's position information is then transmitted to the fire control system by a coordinate system. Frequently the coordinate

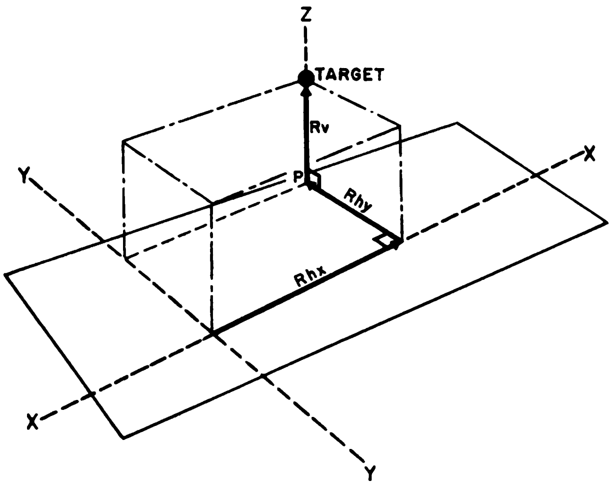


Figure 7-5.—Three-dimensional rectangular coordinate system. 55.132

system used by the search radar must be converted to the one used by the fire control system. Sometimes the coordinates must be modified to compensate for the distance between stations aboard ship.

COORDINATE CONVERSION.—The coordinate system serves merely as a convenient device to describe the location of a target. The location of a target does not change when we employ a different coordinate system to describe it. In figure 7-6 we have located a point in each quadrant. Both rectangular and polar coordinate are given for each point's location. This is possible since both systems have the same frame of reference. When a point is plotted by one coordinate system, the other coordinate system's coordinates may be measured. This is a graphic method of conversion. There are formulas that will convert coordinates, but we will not go into them here.

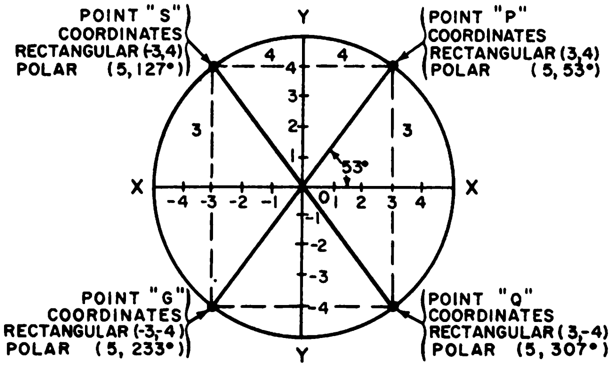


Figure 7-6.—Location of points by rectangular and polar coordinate system. 55.133

TRANSLATION OF AXES.—A coordinate system provides the information describing target's position in a form that can easily be transmitted. As you know, the coordinates are measured with respect to a reference point. When the station receiving the target's position information has its own reference point, the relationship between the two reference points must be established. If the distance between the reference points is measured by linear values, it is called translation of axes. Translation of axes is shown in figure 7-7.

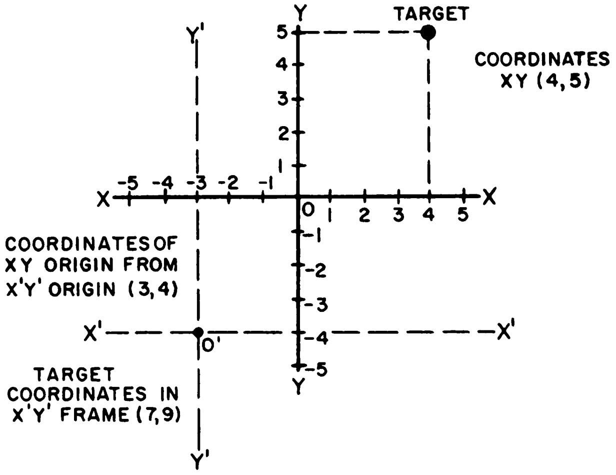


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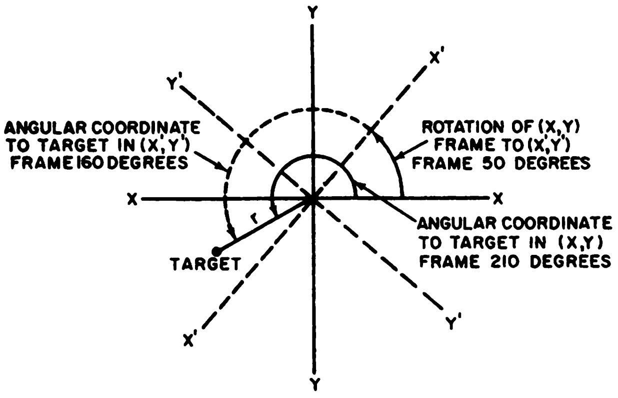
Figure 7-7.—Translation of reference frame.

In the example shown, the origin, O, is 3 units to the right along the X' axis and 4 units along the Y' axis above the origin O'. Therefore, the coordinates of O with respect to the origin O', are (3, 4). The location of the target, with respect to the O origin, is established by the coordinates (4, 5). The location of the target, with respect to the O' origin, is the summation of the coordinates between the origins and the target's coordinates with respect to O origin. In this example, the target's coordinates, with respect to origin O, are (7, 9).

ROTATION OF AXES.—When the frame of reference is transformed angularly, as shown in


Y
X'
Y'
ANGULAR COORDINATE TO TARGET IN (X',Y') FRAME 160 DEGREES
ROTATION OF (X,Y) FRAME TO (X',Y') FRAME 50 DEGREES
X
X
r
ANGULAR COORDINATE TO TARGET IN (X,Y) FRAME 210 DEGREES
TARGET
Y'
X'
Y

55.135

Figure 7-8.—Rotation of reference frame.

figure 7-8, it is called rotation of axes. The axes rotate about the origin. Therefore the range to the target (r) remains constant. The target's angular coordinate from the rotated axes (X', Y') is the summation of the angular coordinate from the X and Y axes and the amount of rotation of the axes. When both translation and rotation are performed, a combination of both procedures is necessary.

FIRE CONTROL COORDINATE SYSTEMS

There are many variations of the polar and rectangular coordinate systems. The type of coordinate system used depends on the information available and the ease of mechanizing that information. In fire control, two types of polar and one type of rectangular coordinate system are employed.

The SPHERICAL coordinate system (fig. 7-9) is a polar coordinate system. The ship is in the center of an imaginary sphere, whose radius is equal to range. The coordinates used to express target's position are:

1. Bearing angle (B) measured from own ship's centerline
2. Elevation angle (E) measured from the reference plane
3. Range (R) measured along the line of sight

The CYLINDRICAL coordinate system (fig. 7-10) is also a polar coordinate system. The ship is in the center of an imaginary cylinder whose radius is equal to horizontal range. The height of the cylinder is equal to vertical range. The coordinates used to express target's position are:

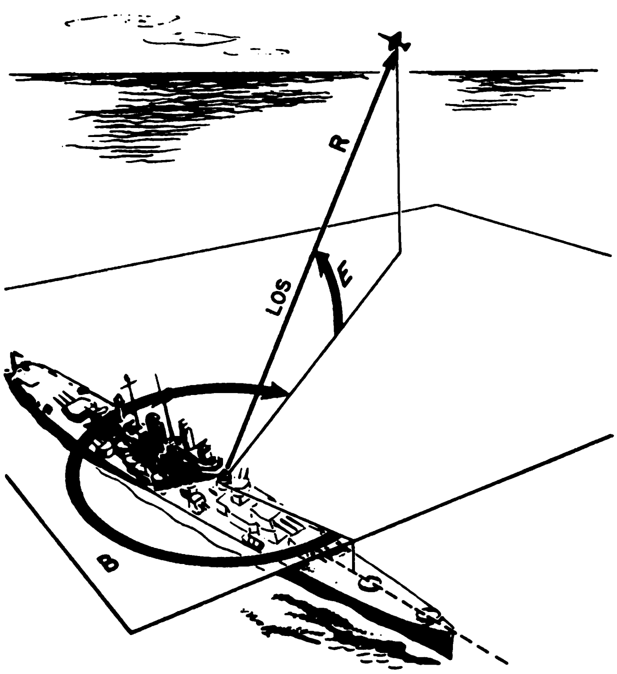


Figure 7-9.—Target position in spherical coordinates. 55.136

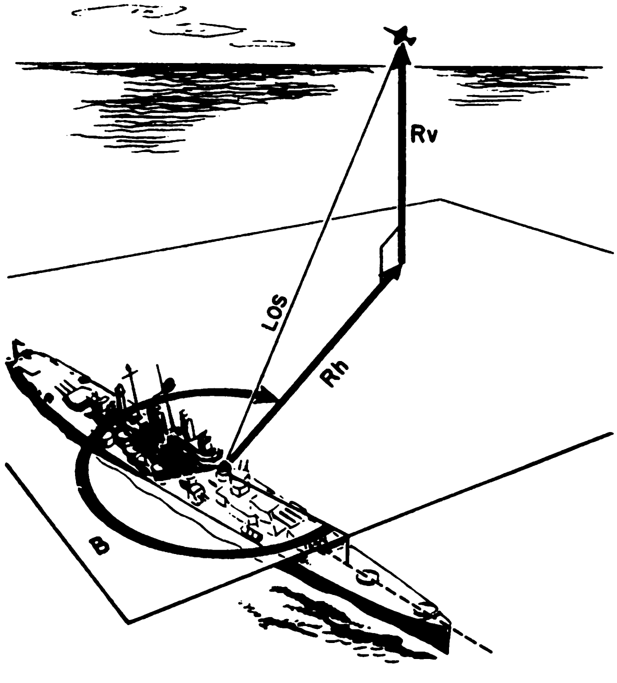


Figure 7-10.—Target position in cylindrical coordinates. 55.137

1. Bearing angle (B) measured from own ship's centerline
2. Horizontal (or deck) range component (Rh) measured in reference plane
3. Vertical (or normal) range component (Rv) measured perpendicular to the reference plane

The CARTESIAN coordinate system (fig. 7-11) is a rectangular coordinate system. The quantities used to express target's position are:

1. Horizontal range component in the east/west axis (Rhx)
2. Horizontal range component in the north/south axis (Rhy)
3. Vertical range component (Rv) measured perpendicular to the reference plane

In each coordinate system the geometrical quantities of range, bearing, and elevation describ target's position. Any one of the three coordinate systems can be used with any one of the four frames of reference. In all cases the reference point is contained within own ship or the destructive package.

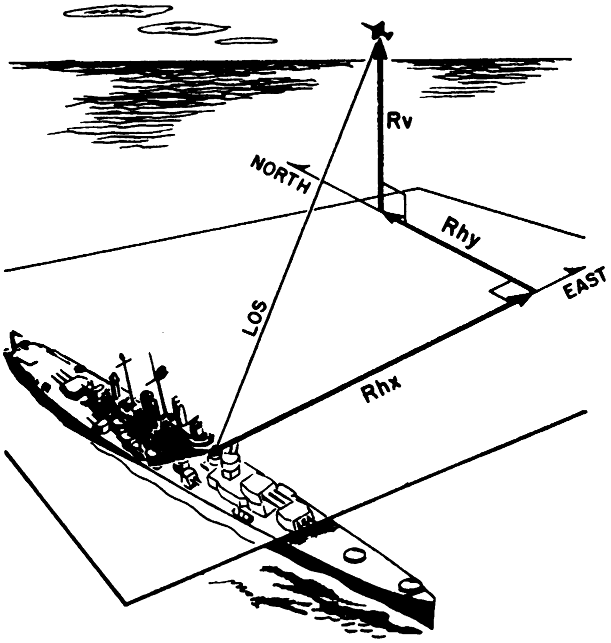


Figure 7-11.—Target position in Cartesian coordinates. 55.138

FIRE CONTROL PROBLEM

The basic fire control problem was stated in the FT3 training course. It showed that most of the factors in the problem arise from two basic causes: (1) the trajectory is not a straight line, and (2) a lapse of time takes place between firing and impact or burst. Therefore, the fire control problem consists mainly of measuring and predicting motions and forces acting during the time of flight. Motions and forces are vector quantities. The problem's solution then is mainly the resolution, addition, and subtraction of vector quantities. The vectors must be related by common axes. The axes (such as the line of sight (LOS) and the line of fire (LOF)) are furnished by a coordinate system within a frame of reference.

The basic fire control problem takes many forms. The problem is correctly solved when the LOF intersects the target at the end of the time of flight (Tf). This involves the prediction of the target's position at the end of the Tf, and the ballistic factors affecting the trajectory.

First, let's look at the problem of predicting target's future position. The target's future position is the position the target will occupy at the end of the Tf. The target's future position is established by the prediction angle measured with respect to the LOS. The prediction angle is derived from the prediction of relative motion between own ship and target during the Tf. The approaches taken to solve the relative motion prediction problem can be placed into three broad, general classifications.

The first approach is based on the linear rate of relative motion. Later we will see that linear rates can be converted to angular rates. The mathematical solution to the problem covered in this course will use linear rates. This is the approach taken by most fire control systems.

The second approach is based on the angular rate of relative motion. The angular rates are the timed angular movements of the LOS. The LOS is the connecting link between own ship and the target. The GFCS Mk 63 is an example of an angular rate system. This approach to the relative motion problem is generally used by short-range systems.

The third approach is based on the relative position of own ship, target, and weapon. In this approach, the weapon must be controllable after firing. A triangle is formed, one side being the LOS, another side being a line between own ship and the weapon, and the third side being a line between the weapon and the target. When the LOS and the line to the weapon coincide, the triangle is closed and the correct prediction has been made. This approach is generally used with missiles and torpedoes. However, the weapon launcher must be initially positioned by a prediction generally computed by the first approach.

The choice of weapon—missile or gun—is a major factor in the fire control problem. The guided missile is controllable in flight; a projectile is not, but its flight path is predictable. Therefore, for the projectile it is necessary, before firing, to make predictions for the entire time of flight. The guided missile requires predictions for only the initial phase of the flight. This is the portion of the flight between the instant of launch and the time when the missile's guidance system takes control of its flight path. Thus the major difference between the guided missile problem and the gun problem in a fire control computer is the length of time for which predictions are necessary. However, the basic problem remains the same, regardless of the type of weapon.

The solution to the fire control problem covered here is for an analog computer using linear rates. The advantage of linear rates is that they are constant for any target with a constant course and speed. Angular rates vary with range.

The linear rate approach allows us to use the simpler surface problem as a foundation for the air problem. We will associate the problem with the Rangekeeper Mk 8 and Computer Mk 1A. The problem will then be tied to basic computing mechanisms. A review of basic mechanisms will show other mechanisms that perform the same functions.

STANDARD FIRE CONTROL SYMBOLS

The fire control symbol system establishes a uniform pattern for all quantities used in surface, antiaircraft, and underwater fire control problems. This includes gun, missile, and underwater weapons found aboard ship. Symbols are not new to you; mathematics, electricity, and electronics use them extensively. The need for symbols is obvious. Symbols are concise, specific without ambiguity, and easily recognized and understood. The problem will be expressed in symbols, for they are the language of the Fire Control Technician.

A description of the symbol system will not be covered in this course, but the basic symbols and their modifiers are listed. The fire control symbols are made up of these basic symbols and their modifiers. The symbols define the quantities they represent. The fire control symbols, their construction, and definitions are covered in OP 1700, Volumes 1, 2, and 3.

Many of the publications you will read still use the former fire control symbols. We will list both the present and the former basic symbols in this chapter. The problem's solution is expressed in the former symbols. By comparing the list of basic symbols, the former symbols can be converted to the present symbols.

In the present system of fire control symbols, all common features of the problem are divided into classes of quantities, (such as bearing, elevation, and range). We can rigidly define a quantity by:

1. Class
2. Where it is measured (such as in the deck plane, future position, relative or true, LOS or LOF)
3. How it is measured (such as linear or angular rate)

The result of this approach is a uniform, flexible system. This symbol system can be applied to all quantities in any method of solution to the fire control problem.

Basic Symbols and Modifiers

The basic symbols assigned to represent the basic geometrical quantity in each class, and the letters and numerals used to modify these basic symbols are:

	Basic Symbols
A	Angular Movement (Elevation)
B	Bearing
C	Course
D	Rate of
E	Elevation
Ei	Level
I	Inclination
J	Jump
L	Sight Deflection
M	Linear Movement
P	Gun Parallax Displacement
Ps	Director Parallax Displacement
R	Range
S	Angular Movement (Lateral)
T	Time
U	Velocity
V	Sight Angle
W	Wind Rate
Z	Crosslevel

	Modifiers
a	apparent
b	bearing
d	deck
g	gun
h	horizontal
i	inclination
k	earth
o	own ship
p	prediction
q	heading
r	range
s	director
t	target
v	vertical
w	wind
x	east-west
y	north-south
z	crosslevel
1	present position
2	future position
3	advance position
4	aiming position
5	fuze

A few examples of symbol construction will give us a better understanding of how the system works.

EXAMPLE 1

DMb = Rate of linear movement in bearing
D = Rate of
M = Linear movement
DM = Rate of linear movement
b = bearing

EXAMPLE 2

Mho = Own ship's speed
M = Linear movement
h = horizontal
Mh = Linear movement in horizontal plane
o = own ship

By substituting t for o, we have Mht, target's horizontal speed.

EXAMPLE 3

Rp2 = Difference between present range and future range
R = Range
p = prediction
Rp = predicted quantity in range
2 = Future position
Rp2 = Predicted quantity to future position in range

EXAMPLE 4

By = True target bearing
B = Bearing
y = North/south axis
By = Bearing measured to north/south axis

EXAMPLE 5

DE = Angular elevation rate
D = Rate of
E = Elevation

All rates are angular unless a linear rate is indicated by the symbol M.

Quantity Modifiers

Besides the geometrical quantities in each class, the portions of these quantities measured to various positions and accounting for various effects are symbolized. Also, in the expression of rates, the frame of measurement of the rate is indicated. These quantity modifiers are applied by enclosing the symbols for the geometrical quantities in parentheses and preceding or following the parentheses with the quantity modifiers. For example, the portion of sight angle Vs accounting for the effect of wind is symbolized by enclosing the sight angle symbol Vs in parentheses, and preceding the parentheses with modifier w (meaning portion accounting for wind), forming symbol w(Vs).

As indicated in the example, in general, when the modifier precedes the parentheses, it defines the correction to the basic quantity due to the effects of the modifier. If the modifier follows the parentheses, it defines the basic quantity corrected for the effects of the modifier.

The meanings of the letters when used as quantity modifiers of geometrical quantities are:

a	advance
b	ballistics
c	computed or generated
d	designated
e	estimated or error
f	function
g	dead time
i	increments
j	computational addition or partial value
k	earth
l	initial
m	relative motion
o	own ship
p	gun parallax
ps	director parallax
q	corrective input or spot
r	rate control
s	inertial or selected
u	initial velocity loss
w	wind

The former symbol system is restricted in its application. The basic symbols are used primarily to rigidly define the quantity, and the modifiers are used to show where and how it is measured.

Former Basic Symbols

A	Target Angle
B	Bearing (of target, unless modified), measured in the horizontal plane
B'	Same as B, but measured in the deck plane
C	Course, measured in the horizontal plane
D	Lateral Deflection (angular measure)
E	Elevation (of target, unless modified), measured in the vertical plane
E'	Same as E, but measured in a plane perpendicular to the deck
F	Fuze Setting

H	Height of Target (normally in feet)
K	K_1, K_2, etc. Constants
L	Level Angle, measured in the vertical plane
P	Parallax
R	Range
S	Speed
T	Time
V	Elevation Prediction (angular measure)
X	Horizontal deflection component of velocity perpendicular to the vertical plane through the line of sight
Y	Horizontal range component of velocity in the vertical plane through the line of sight
Z	Crosslevel Angle

In general, a PRIME (') after a basic symbol indicates the quantity is measured in the plane of the deck of own ship, or in a plane perpendicular to the deck of own ship.

Former Modifying Symbols

b	Of director
c	Before a quantity means the value of that quantity as generated by the mechanism, as opposed to the OBSERVED value of the same quantity. After a quantity means relative to rate control.
d	Before a quantity means a time rate of change of that quantity. After a quantity means in or relative to the deck plane or plane perpendicular to the deck.
e	Elevation
f	Due to standard trajectory
g	Of gun
h	Horizontal projection of
j	Before a quantity means a correction or partial correction to that quantity, usually generated by the mechanism. After a quantity means arbitrary correction (spot) to that quantity.
m	Loss of Initial Velocity
o	Of or due to Own Ship
r	Relative to Own Ship
s	Relative to the line of sight, or in a slant plane. (Since several slant planes may be used, each definition should specify the plane used.)
t	Of or due to target
v	Vertical projection of
w	Of or due to wind
z	Of or due to crosslevel
f( )	Function of the quantity in parentheses
Δ	Before a quantity means change in that quantity during some specific time. Increment of a quantity.
$\int$	Before a quantity means the integral of that quantity
2	After a quantity indicates that it is the predicted value of that quantity for advance position; i.e., for the instant a projectile, which is fired at the present time, hits (bursts for antiaircraft fire).
3	After a quantity indicates that it is the predicted value of that quantity for fuze position; i.e., for the instant a projectile, fired dead time seconds from the present time, hits (bursts for antiaircraft fire).

A few examples of symbol construction will once again give us a better understanding of how this system works.

EXAMPLE 1

RdBs = Linear deflection rate
R = Range; when used before a rate symbol, indicates a linear rate
d = Time rate of change
B = Bearing
s = Line of sight

EXAMPLE 2

So = Own ship's speed
S = speed
o = own ship

EXAMPLE 3

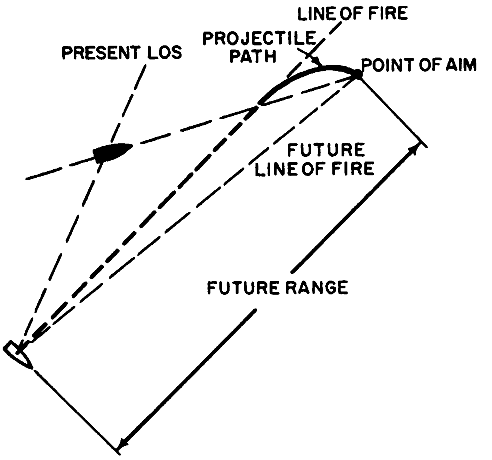
Sh = Target's horizontal speed
S = Speed
h = horizontal

THE SURFACE RELATIVE MOTION PROBLEM

Fire Between Moving Ships

The LOF must be correct for own ship and target motion. Our first task, then, is to resolve all motion into movement of the target into coordinates based on the present position of the target. This can be done by considering the motion of both own ship and target as motion of the target relative to own ship. The present position of the surface target is based on two coordinates—target bearing and range.

If we make a few preliminary assumptions, the problem will be much easier to solve—the complicating factors can be added later. If we



55.139
Figure 7-12.—Basic fire control problem.

assume a stable reference plane, zero wind velocity, and the elimination of parallax by locating the director and gun at the same theoretical point on the ship, the basic problem becomes that of figure 7-12.

Relative Motion

It must be emphasized that relative motion is affected by changes in own ship's course, Co. This is logical because own ship's motion necessitates a greater or lesser rate of director train during the time your ship is changing course. If not compensated for, this would cause an error in the measurement of target motion. Therefore, relative motion is measured in true bearing coordinates and then modified by the own ship's course input, Co, to give relative target bearing, Br.

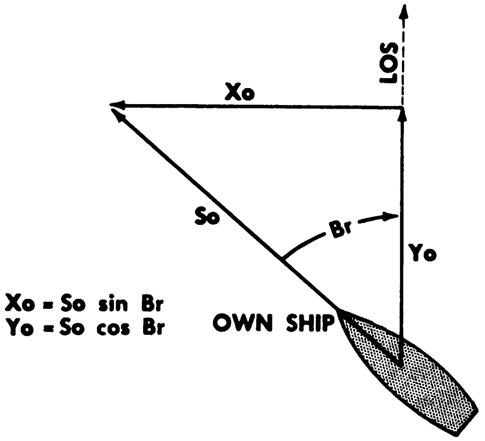
Let's size up the problem for a moment by starting with the data received from the director. The director, as you know, measures the range and bearing of the target PRESENT POSITION, the actual spot where the target is at any time. But what the rangekeeper does is to take this information, along with estimated target course and speed, and predict where the target will be after Tf has elapsed. That is, the rangekeeper must compute the FUTURE TARGET POSITION relative to own ship, and the line of fire (LOF) to the future target position. In the surface problem, the LOF is determined by computing the gun elevation and train orders (E'g and B'gr).

Own Ship Motion

Think for a moment about the effect of own ship motion on the projectile. When the ship is stationary with no wind present, the projectile has only one velocity when fired—its initial velocity, I.V. But when the ship is moving, the projectile has two velocities: the I.V. and own ship speed, So. Own ship motion will be transferred to the projectile at the instant it's fired, and will act on it throughout its flight. Obviously, the point of aim of the gun must be changed in order to hit the target. And, of course, these changes will appear in sight angle, Vs and sight deflections, Ds.

For example, if own ship is moving toward the target the gun must be depressed in order to keep from over-shooting. That is, Vs must be DECREASED. Or, if own ship is moving leftward relative to the target, the gun must be trained right to keep from missing to the left—Ds must contain a RIGHT correction.

Own ship motion is always represented by a vector whose magnitude is So (own ship speed), and whose direction is Br (relative target bearing) measured from the ship's centerline clockwise to the line of sight, LOS, as shown in figure 7-13. You will recall that So (own ship speed) is received from the pitometer log, and that Br (relative target bearing) is measured by the director.



55.140
Figure 7-13.—Components of own ship motion.

A look at the figure will show that So has two effects: that of shortening or lengthening range, and that of deflecting the projectile left or right. To find the effect of own ship movement on the range and on the deflection of the projectile, you have to break own ship speed So into components along and across the LOS. These components are Xo and Yo. The DEFLECTION COMPONENT Xo is calculated by multiplying So by sin Br, and the RANGE COMPONENT Yo is found by multiplying So by cos Br.

If you multiply Yo by Tf, and affix the correct sign, you have the correction for range due to own ship movement. Of course, this neglects air resistance; as the shell moves at speed Yo (in addition to I.V.), it will have to push through the air and will be slowed down. So the total error will be less than Tf x Yo. By the same reasoning, the value of the linear deflection would be Xo x Tf neglecting air resistance.

Target Motion

Target motion can be treated in exactly the same way as own ship motion. The target vector has a magnitude of target speed (S or Sh) and a direction measured by the target angle, A. Target angle is measured clockwise from the bow of the target to the LOS as indicated in figure 7-14.

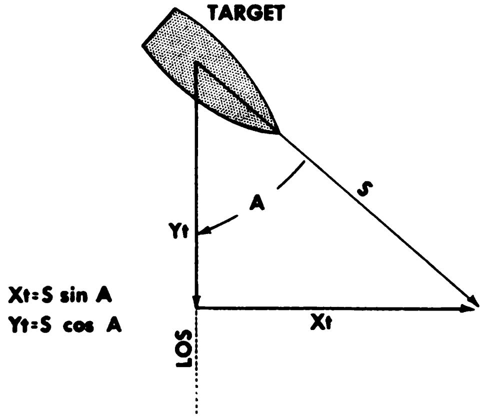


Figure 7-14.—Components of target motion.

The target-speed vector is broken down into components along and across the LOS the same as the own ship speed vector. These components are the target deflection component (Xt) and the target range component (Yt).

As shown in figure 7-14, Yt is obtained by multiplying S by cos A, and Xt by multiplying S by sin A. You can solve the range and deflection errors created by target motion by multiplying each by Tf. Of course the corrections would carry opposite signs to those of the errors.

Solving Own Ship and Target Motion

Now you can lay out the own ship and target motion vectors on the same diagram showing all their references and angles as demonstrated in figure 7-15. This figure shows the relationship of the own ship and target vectors, along with all angles, plotted with respect to the LOS and true north. You can get a firm picture in mind of how these angles are formed by studying the plot of the angles.

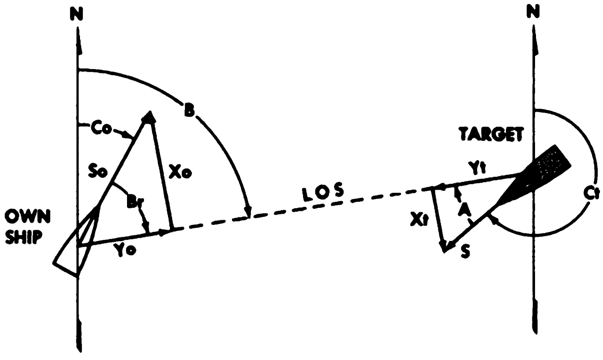


Figure 7-15.—Plot of own ship and target motion. 55.142

The relationship between true bearing B, with respect to relative bearing Br, is expressed in the formula:

$$B = Br + Co$$

Notice the reference lines involved; Co establishes the bow of own ship with respect to the true north, Br establishes the LOS with respect to the bow of own ship, B establishes the LOS with respect to the true north; therefore B must be the sum of Br and Co.

The business of calculating A is a little tricky, but quite simple once you catch on. The formula for target angle A is:

$$A = (B + 180) - Ct$$

Notice that B is measured from north clockwise to the LOS at own ship, NOT from north clockwise to the LOS at the target. This is why you must add 180° to B to make the formula work out right. Another way to look at A is that it is own ship's relative bearing as measured by the target.

To summarize the own ship and target motion calculations, study figure 7-16. Here, the own ship and target vectors along and across the LOS are superimposed on the own ship and target component solvers.

The angle gear of the target component solver is positioned by angle A which is made up from Br, Co, and Ct by the differentials shown in the figure. Then S and A position the vector gear and the compensating differential to give the vector input. The outputs at the component-solver racks are Xt and Yt.

The own ship components are solved exactly the same way, except that Br and So position the inputs to the own ship component solver, and the outputs are Xo and Yo as indicated.

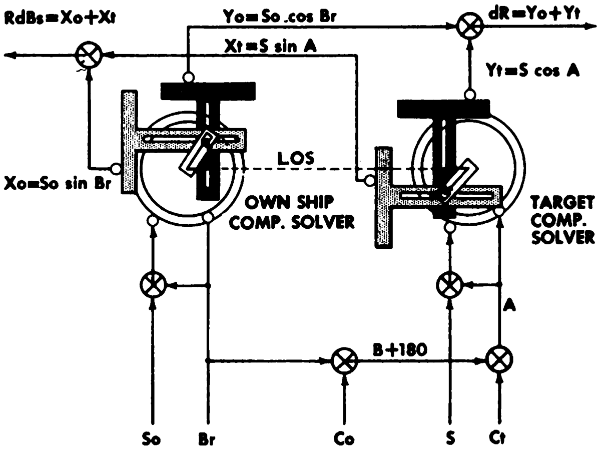


Figure 7-16.—Solving own ship and target motion.

55.143

Linear Rates

The next step in solving the surface fire control problem is adding up the components you have just computed. When Yo and Yt are ADDED you get LINEAR RANGE RATE dR, which is a particularly useful quantity used in rangekeeper calculations because it tells the total speed with which range is changing.

Likewise, when Xo and Xt are added you get the LINEAR DEFLECTION RATE RdBs, which is measured at the target. After being converted to mils it tells the speed with which the deflection angle is changing.

Remember that the linear range rate and linear deflection rate are expressed by the following additions:

$$dR = Yo + Yt \text{ knots}$$
$$RdBs = Xo + Xt \text{ knots}$$

To sum them up in one small statement, these quantities represent the time rate of change of range and linear deflection.

The plus signs in the above expressions indicate algebraic addition. These components can be either positive or negative in accordance with the arbitrary rule that a range component of own ship or target motion (the correction) is considered PLUS if it tends to INCREASE range, and MINUS if it tends to DECREASE range.

Similarly, the deflection component of own ship or target motion (the correction) is considered PLUS if it tends to INCREASE the relative target bearing, or MINUS if it tends to DECREASE the relative target bearing. You can tie this rule together in the chart of figure 7-17.

A linear rate measured in knots (nautical miles per hour) is too large a value both in distance and time for our use. We must modify it to yards per second, as shown in figure 7-18. To convert a rate from knots to yds/sec, we multiply by the constant 0.563. Thus linear range rate in yds/sec equals

$$Yo + Yt \times 0.563$$

Range rate is always linear as range is always linear.

Deflection rate must not only be modified to yds/sec but must also be converted to an angular rate. Angular deflection rate (dBs) has two forms: Mils when used in the correction to Ds, and minutes of arc when used in the correction to B' gr and B' r.

Let's look at the mil and see what it is and where it comes from. First, a mil is a form of angular measurement. A radian is an angle formed by two radii of a circle when the arc they subtend is as long as the radius. The radian has an angular value which is constant (57.3°) and a linear value (the radius) which varies with the circle's radius. Once again the value is too high for our use so we take 1/1000 of it, which is the mil. The mil is equal to 3.43 minutes of arc or 1/1000 the radius of a circle. In our case, range would be the radius of the circle or arc (fig. 7-18).

To convert linear deflection rate in yd/sec to an angular rate in mils per second, we divide

COMPONENT	ANGLE Br OR A	SIGN OF ERROR	SHOT FALLS (ERROR)	CORRECTED FOR BY	SIGN OF CORRECTION
Y (RANGE)	0-90 270-0	PLUS	OVER	DEPRESSING	MINUS
	90-180 180-270	MINUS	SHORT	ELEVATING	PLUS
X (DEFLECTION)	0-180	MINUS	LEFT	TRAIN RIGHT	PLUS
	180-360	PLUS	RIGHT	TRAIN LEFT	MINUS

Figure 7-17.—Summary of range and deflection components.

55.144

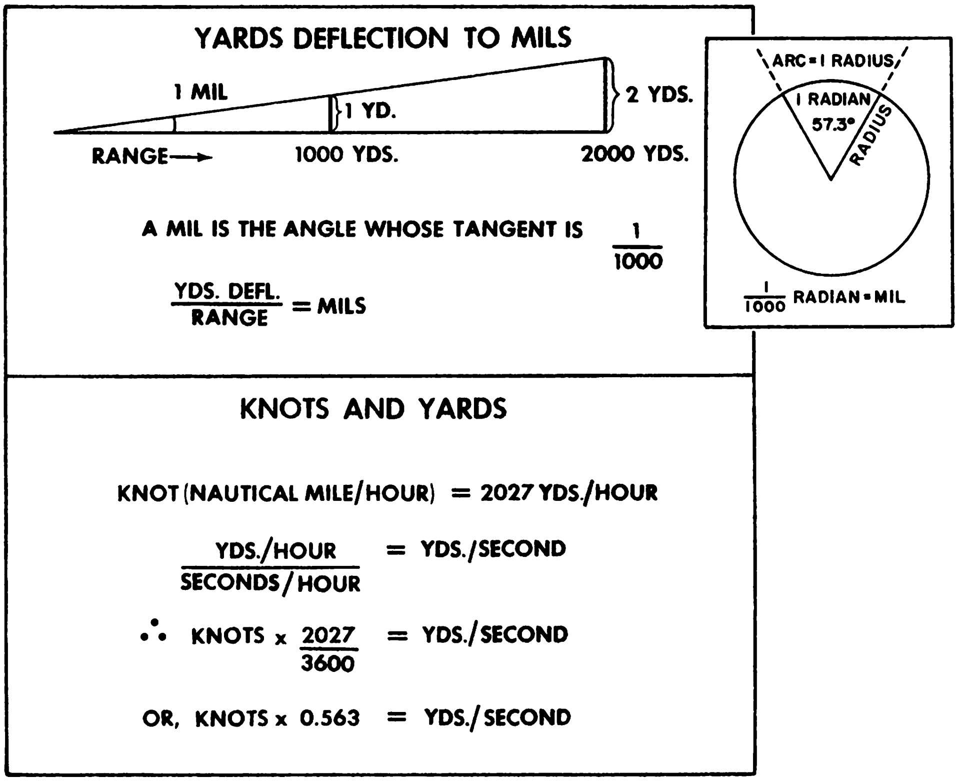

YARDS DEFLECTION TO MILS
1 MIL
1 YD.
2 YDS.
RANGE⟶
1000 YDS.
2000 YDS.
A MIL IS THE ANGLE WHOSE TANGENT IS $\frac{1}{1000}$
$\frac{\text{YDS. DEFL.}}{\text{RANGE}} = \text{MILS}$
ARC = 1 RADIUS
1 RADIAN
57.3°
RADIUS
$\frac{1}{1000}$ RADIAN = MIL
KNOTS AND YARDS
KNOT (NAUTICAL MILE/HOUR) = 2027 YDS./HOUR
$\frac{\text{YDS./HOUR}}{\text{SECONDS/HOUR}} = \text{YDS./SECOND}$
$\therefore$ KNOTS x $\frac{2027}{3600}$ = YDS./SECOND
OR, KNOTS x 0.563 = YDS./SECOND

Figure 7-18.—Mils, knots, and yards.

55.145

the rate by the range. The range is the radius of the arc and the rate the tangent to the arc, as shown in figure 7-18. To convert the rate to minutes of arc per second, we first convert it to mils per second and then multiply by the number of minutes (3.43) in a mil.

RANGE PREDICTION

Since own ship and target are continually changing positions while the projectile is in the air, it is necessary to predict the future target position from changes in range rate dR and changes in linear deflection rate RdBs. These computations are in addition to the regular trajectory corrections.

Figure 7-19 shows what happens to range during time Tf. The range changes, which means that you must determine exactly how much it will change and then add the total change to present range. This addition gives advance range R2.

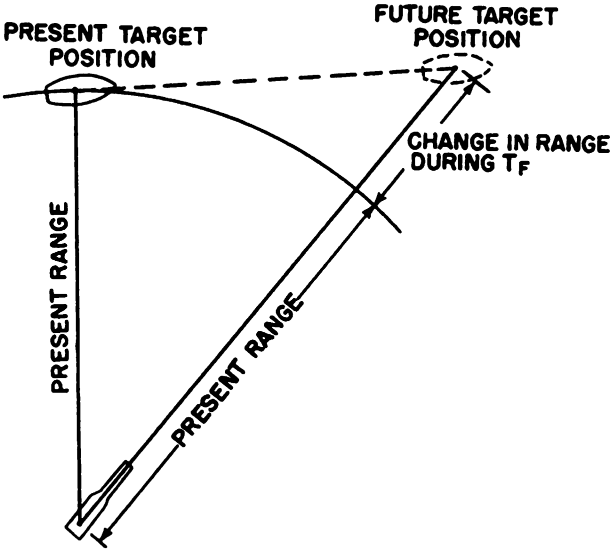
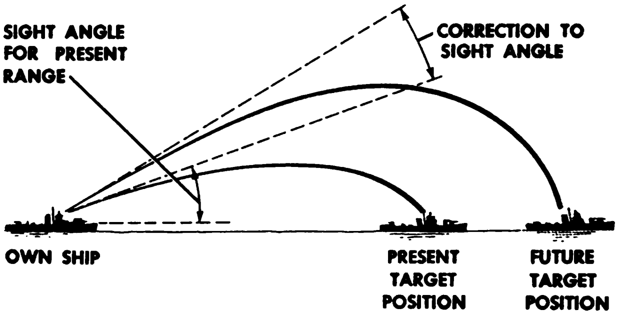


Figure 7-19.—Range prediction. 55.146

Once R2 is determined, it is easy to compute the sight angle, Vs. Back when you studied the range tables, you found that for every given range there's a corresponding value of Vs (fig. 7-20). You also found that Vs will increase or decrease with range, but not directly. So the logical thing to do would be to compute Vs from a Vs cam which is positioned by R2. Almost all of the surface rangekeepers compute Vs with a cam; in any event, a cam cut to some function of Vs and R2 will be used.

Now in this seemingly roundabout way of getting Vs, the big problem becomes the calculation of the total change in range—that is, to determine range prediction due to own ship and target motion Rt. It can be computed in a number of ways, but regardless of how it's done, it will always seem a little difficult.

You will recall that dR tells the speed with which range is changing, so at first thought it might seem logical to multiply dR by Tf to give total change in range. Your answer would be correct only for slow-moving targets, because



55.147

Figure 7-20.—Sight angle for a moving target.

the value of Tf was taken to present range—the only available value of range you have.

To be correct, Rt must represent the amount the range changes (due to own ship and target motion) during the time (Tf) it takes the projectile to get to the target. With this in mind, it should be obvious that you can't compute Rt from the Tf based on the range to present target position. Instead, a Tf based on a certain range nearly equal to R2 should be used; however, for all practical purposes, a Tf based on R2 is used.

But here's the catch—how in the world can you calculate Tf based on R2, when you need Tf to calculate Rt to get R2? Sure, it sounds like a vicious circle, and, strange as it may seem, it actually is!

You can get the correct value of Tf by a regenerative process which is done by feeding the output back into the input of a range-prediction computer. This is really the same as putting in a series of substitutions, which is carried on indefinitely in the machine until the answer—Rt and, in turn, Tf—is correct.

An example will probably give you the idea better:

(1) Find Tf to present range.
(2) Multiply quantity (1) by dR to get the first approximation of Rt.
(3) Add quantity (2) to present range to get the first approximation of R2.
(4) Find Tf corresponding to the first approximation of R2, (3).
(5) Multiply quantity (4) by dR to get the second approximation of Rt.
(6) Add quantity (5) to present range to get the second approximation of R2.

This could be continued indefinitely, although two substitutions would be accurate enough.

Such a problem is worked by the machine shown in figure 7-21. The Tf cam and multiplier

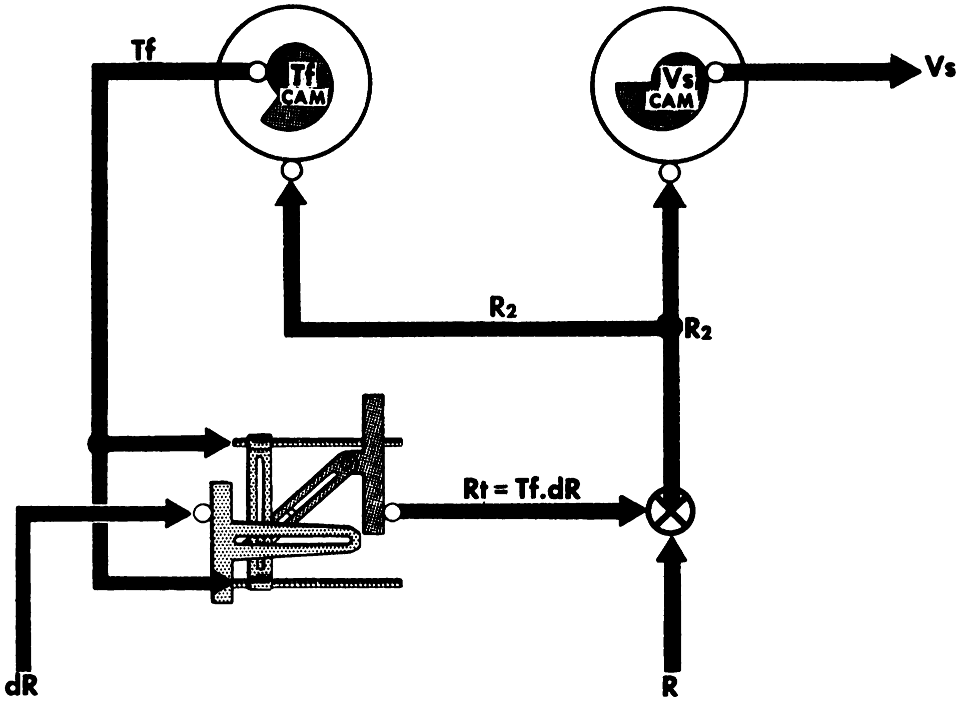


Figure 7-21.—Computing Vs with a simple ballistic computer. 55.148

solve the equation for range prediction due to own ship and target motion:

range prediction = (Yo + Yt) Tf
or, Rt=dRxTf

which is added to present range R in the differential to give R2. Then R2 drives the Vs cam to produce the quantity Vs, which you have spent such a long time trying to find.

DEFLECTION PREDICTION

In solving for range prediction you really killed two birds with one stone, because in doing so, you also solved for the Tf. And since Tf is used to solve deflection prediction due to own ship and target motion, Dt, half of the deflection problem is already worked out.

But before we get into the details of solving deflection prediction, let's first review the problem and see what deflection actually is. In the most simple case shown in figure 7-22, sight deflection Ds is the angle the gun must be offset from the LOS to allow for own ship and target motion during Tf. In short, you have to PREDICT how much to LEAD the target so that the shell and target will meet at a point at some future time.

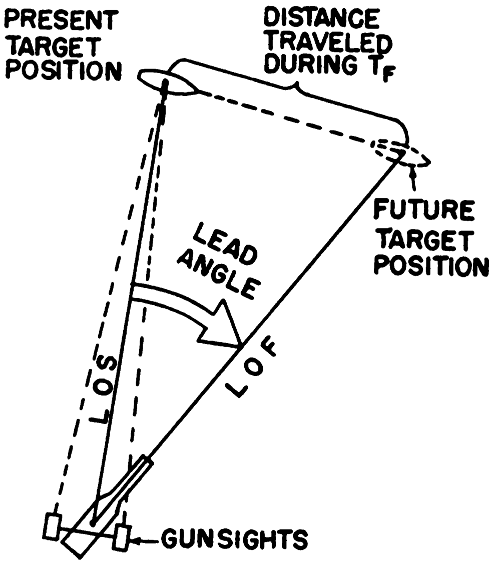


Figure 7-22.—Sight deflection for lead. 55.149

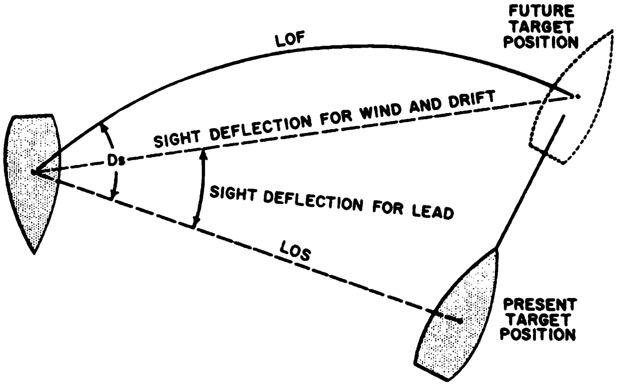

LOF
FUTURE TARGET POSITION
SIGHT DEFLECTION FOR WIND AND DRIFT
Ds
SIGHT DEFLECTION FOR LEAD
LOS
PRESENT TARGET POSITION

Figure 7-23.—Sight deflection Ds. 55.150

Of course, you also have to correct Ds for things such as drift and wind. Therefore Ds includes all the corrections shown in figure 7-23 so

$$Ds = Dt + Df + Dw$$

where Dt is the deflection necessary to correct for own ship and target motion, Df is the correction for drift, and Dw is the correction for wind.

Now let's calculate Dt. The first step is to multiply RdBs (linear deflection rate in yards/second) by Tf as shown in figure 7-24, which gives linear deflection prediction at the target in yards. Then to convert this value to mils just divide by R2 in thousands of yards. Therefore, Dt is equal to:

$$Dt = \frac{RdBs \times Tf}{R2} \text{mils.}$$

Figure 7-25 shows a simplified schematic diagram of the mechanical units used to solve Dt in a rangekeeper.

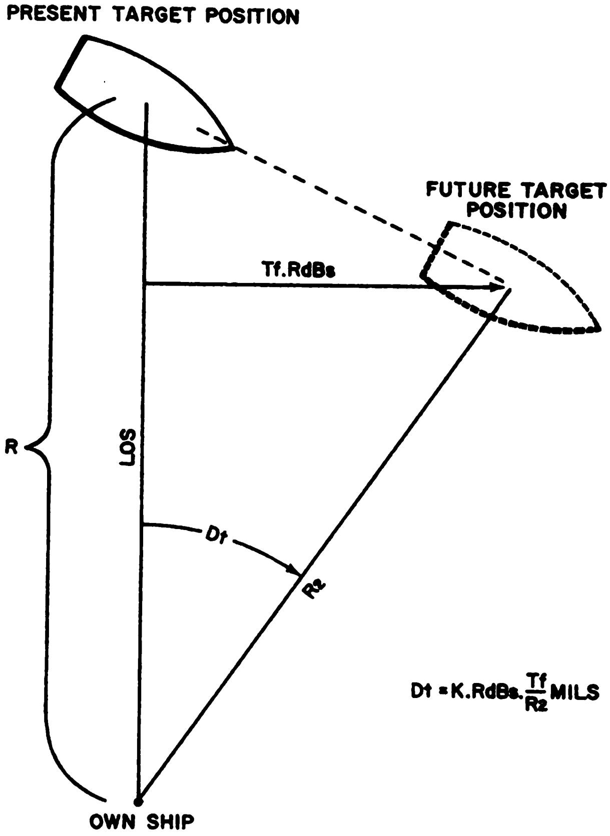


Figure 7-24.—Deflection prediction for own ship and target motion. 55.151

RANGE EFFECT OF DEFLECTION AND I.V. CORRECTION

The simple formula you used to calculate R2 (and Vs) is not always accurate enough for rangekeepers and computers used in main battery and antiaircraft plotting rooms, because deflection prediction introduces a RANGE ERROR (see fig. 7-26). For small deflection angles this error is negligible, but when targets move fast the

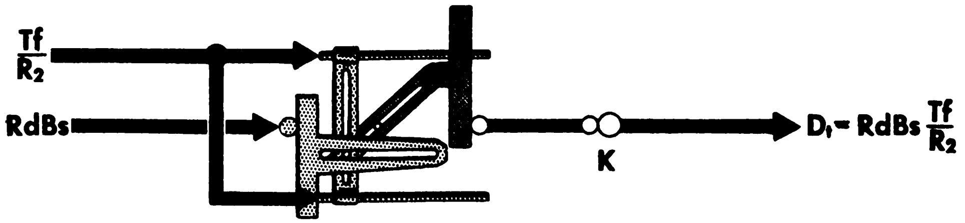


Figure 7-25.—Computing Dt.

55.152

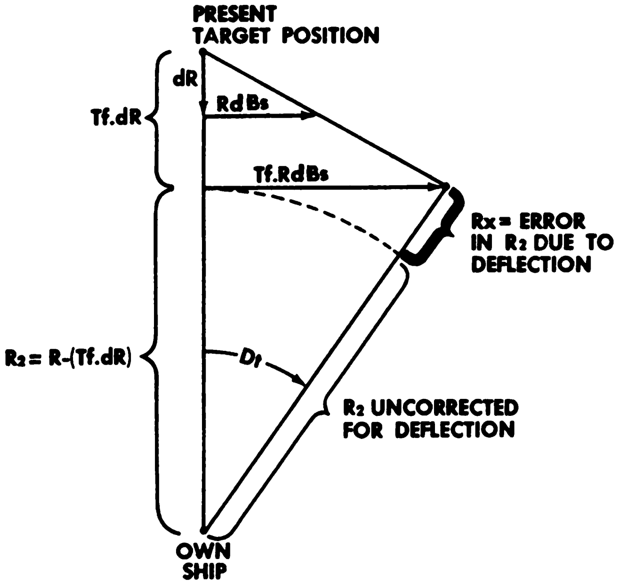


Figure 7-26.—Error in Rz due to deflection.

deflection is increased and so the error in R2 grows larger. A study of the diagram will reveal that where no deflection is present the error is zero.

The correction for range effect of deflection is called the range prediction due to deflection, and is represented by Rx. Rangekeepers make up Rx in a number of different ways. Even so, Rx will always be based on the fact that it is nearly proportional to R2 times $(Dt)^2$, where Dt is mils deflection due to own ship and target movement.

Some rangekeepers go a little further by taking a new value (Dtw) based on the deflection prediction due to wind as well as for own ship and target motion (Dtw=Dt+Dw), exclusive of drift, and substitute this value for Dt. Then you can more accurately write:

$$Rx=R2x(Dtw)^2.$$

But, like most problems in fire control, this problem grows a bit more complicated because, in actual practice, the rangekeeper also solves the range prediction to compensate for changes from initial velocity (Rm), in the same mechanism. Of course, this is more practical from the construction standpoint because it eliminates an extra multiplier which would otherwise be necessary if Rx and Rm were solved separately.

A computer that determines range prediction due to I.V. changes, deflection due to wind, and deflection due to own ship and target motion is shown in figure 7-27.

Take one thing at a time, starting with Dtw. First, Dtw is squared according to the basic formula, $Rx = R2\ (Dtw)^2$, in a cam to give partial range prediction due to cross wind and own ship and target motion, jRx, which is equal to $(Dtw)^2$. Then jRx is added to partial range prediction due to I.V. change, jRm, and the sum (jRmx = jRx + jRm) is fed to the multiplier.

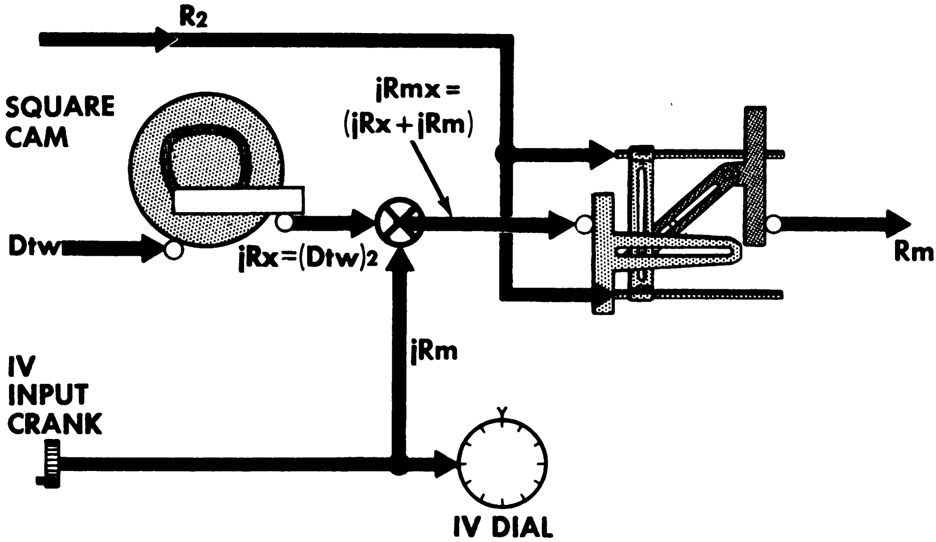


Figure 7-27.—Range prediction due to I.V. changes, wind, and deflection.

55.154

NOTE: The "j" preceding the symbols indicates partial correction.

Finally jRmx is multiplied by R2 in the multiplier to give Rmx. In practice, R2 plus some constant is used as the screw input to the multiplier, which is just another trick to get better results.

The I.V. dial is calibrated so that, when you apply a correction in so many feet/second, the proper correction (jRm) is applied to the multiplier input. And when jRm (along with jRx) is multiplied by R2, the result produces the proper range correction due to I.V. change.

WIND CAUSED BY OWN SHIP MOTION

As a ship steams through still air you can feel a breeze which has the same effect as a wind blowing directly astern. It is called HEAD WIND. The head wind speed is equal and opposite to own ship speed. If own ship is making 10 knots, then the head wind speed is 10 knots.

Consider, for a moment, a projectile that is fired from a moving ship. In addition to all other forces which may be acting upon it, head wind will resist the projectile. Corrections for this head wind must be made to get hits.

Now, in addition, consider what happens when the ship is sailing along with an actual wind present, and this wind makes an angle with the ship's course as shown in figure 7-28. Two wind forces are now acting on the projectile. But here you can think of these two winds as one resultant wind called APPARENT WIND, Swr. The figure shows how true wind and head wind are combined to give Swr.

In computing the effect of apparent wind on the trajectory of the shell, you could proceed as usual except that you would use the apparent wind speed Swr instead of true wind Sw. And, of course, you would use apparent wind direction Bwr instead of true wind direction Bw.

There's a decided disadvantage in using apparent wind angle and speed as rangekeeper inputs, because every time own ship changes course or speed, the value and direction of the velocity vector of apparent wind also changes. You can see why this is true in figure 7-28; assume that own ship changes course with respect to true wind and figure it out for yourself. Most rangekeepers take Sw and Bw as inputs, because they never have to be changed unless true wind changes. The Sw vector is then resolved into Xw and Yw components along and across the LOS, and added to the own ship components.

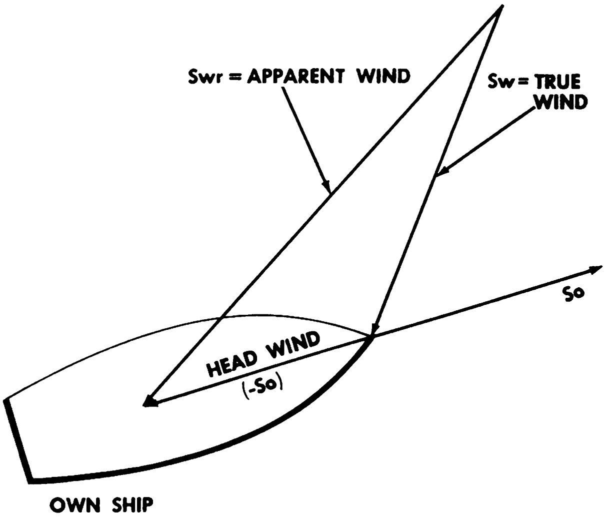


Figure 7-28.—Apparent wind. 55.155

This may look like a roundabout way of calculating corrections for apparent wind, but this method automatically takes care of apparent wind changes due to changes in own ship course and speed. Thus, when you add the true wind and own ship components, you get the apparent wind components ALONG and ACROSS the line of sight. Mathematically you can write:

Xwr = Xw + X0 = component of apparent wind velocity
ACROSS LOS.

Ywr = Yw + Y0 = component of apparent wind velocity
ALONG LOS.

Xwr corrects sight deflection Ds, and Ywr corrects sight angle Vs by correcting advance range R2. At this point you should get an idea of how these wind quantities are treated in an actual machine. Let's start by studying how Dw is made up from Xwr as shown in figure 7-29.

Because the projectile's velocity decreases toward the end of the trajectory, wind has more effect at longer ranges. Consequently, to calculate wind correction, we use a function of ranch such as Tf or Vs, which increases faster than range. The quantity Vs, already present in the machine with a modifying factor of K, is used.

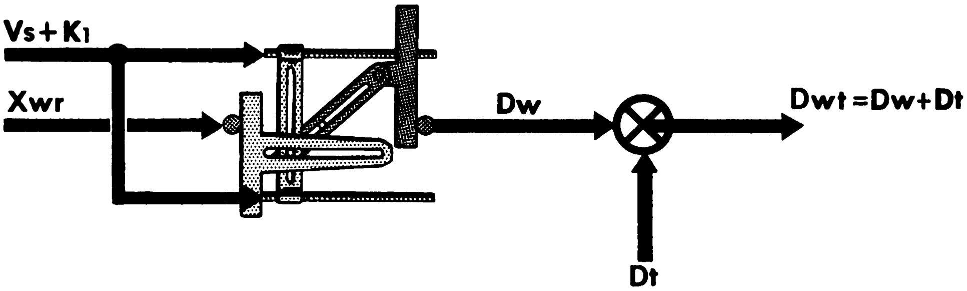


Figure 7-29.—Computing deflection prediction due to wind and own ship and target motion.

The K factor's value will vary as the range changes, and is dependent on the shape and weight of the projectile. Figure 7-29 shows the deflection wind rate, Xwr, multiplied by a quantity, Vs + K1, which is a function of advance range and therefore of Tf. This gives us the deflection wind prediction Dw.

Dw is then added to Dt in a differential to make up deflection prediction due to wind and own ship and target motion, Dtw (fig. 7-29).

Next, see how Ywr is treated. Range prediction due to wind (Rw) is solved in the SAME MULTIPLIER that computes Rt, which of course saves a multiplier. This multiplier is called the RANGE PREDICTOR. Its output is range prediction due to own ship and target motion and wind, Rtw, which is equal to Rt plus Rw; however, neither Rt nor Rw appear SEPARATELY in a rangekeeper, because the multiplier computes them simultaneously.

You will recall from figure 7-21 in this chapter that

$$Rt = dR \times tf$$

It is obvious from what has gone before that

$$Rw = Ywr \times Tf$$

The wind rate, Ywr, is modified for the same reasons deflection wind rate was modified.

Figure 7-30 shows how the range prediction, Rtw, is solved. To see how the setup works, first assume that Ywr is zero (no wind correction present). With Ywr at zero the multiplier simply multiplies Tf by dR to give range prediction due to own ship and target motion Rt, which in this case is equal to Rtw.

But with apparent wind present the two rates dR and Ywr are combined in the differential. The combined rates are multiplied by Tf to give Rtw.

COMPUTING SIGHT ANGLE AND SIGHT DEFLECTION

Now you are ready to wind up this business of own ship and target motion, wind, I.V. correction, range and deflection prediction, and make up sight angle (Vs) and sight deflection (Ds) including ALL their corrections. The best way to learn about Ds and Vs is to put all the foregoing diagrams together and study them as a whole. Let's take Ds first.

The Ds computer in figure 7-31 is really just a review of figures 7-25 and 7-29. As you learned earlier, Ds is equal to the SUM of Dt, Dw, and Df. Each of these three quantities is computed separately. Dt is computed in the TARGET DEFLECTION PREDICTOR mulitplier, and Dw is solved in the WIND-DEFLECTION multiplier. But Df is made up a little different than anything you have computed so far.

If you stop to think back it should be apparent that both Vs and Df increase with range, but they increase faster and faster as range increases. Thus, you can say that both Vs and Df vary as functions of R2. Since both are functions of advance range, it follows that Df is equal to some function of Vs which can be expressed mathematically as Df = f (Vs) (fig. 7-31). This formula has a very general meaning; however, it shows that there is a relationship between Df and Vs. And that's all you need to know here, because proper shafting and gearing to take care of constants, do the rest. One machine manufactures Df by subtracting Vs times a constant from a second constant. These constants are built right into the machine so you'll seldom have to worry about them.

Total range prediction is solved with a couple of cams and multipliers, several differentials, and a few gear ratios to take care of constants. You can see the setup in figure 7-32, which again

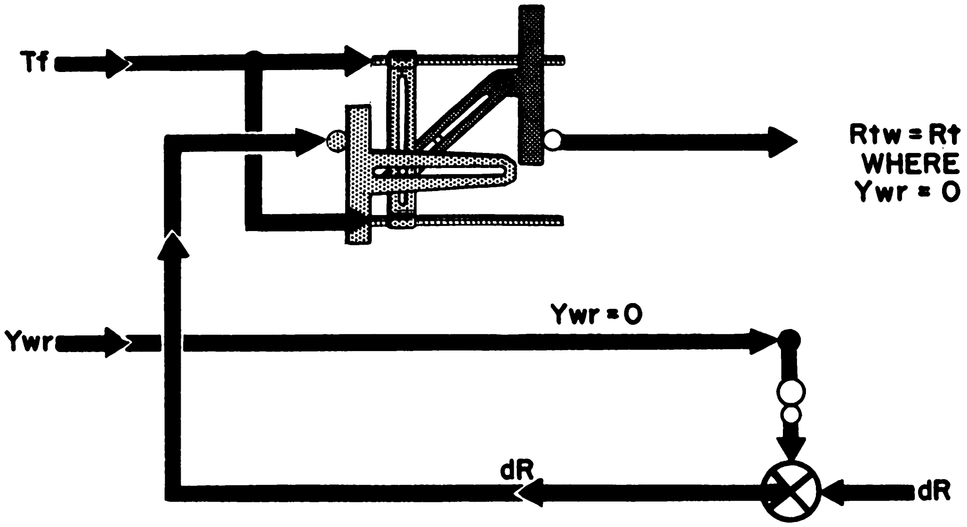


Figure 7-30.—Solving range prediction due to wind and own ship and target motion.

55.157

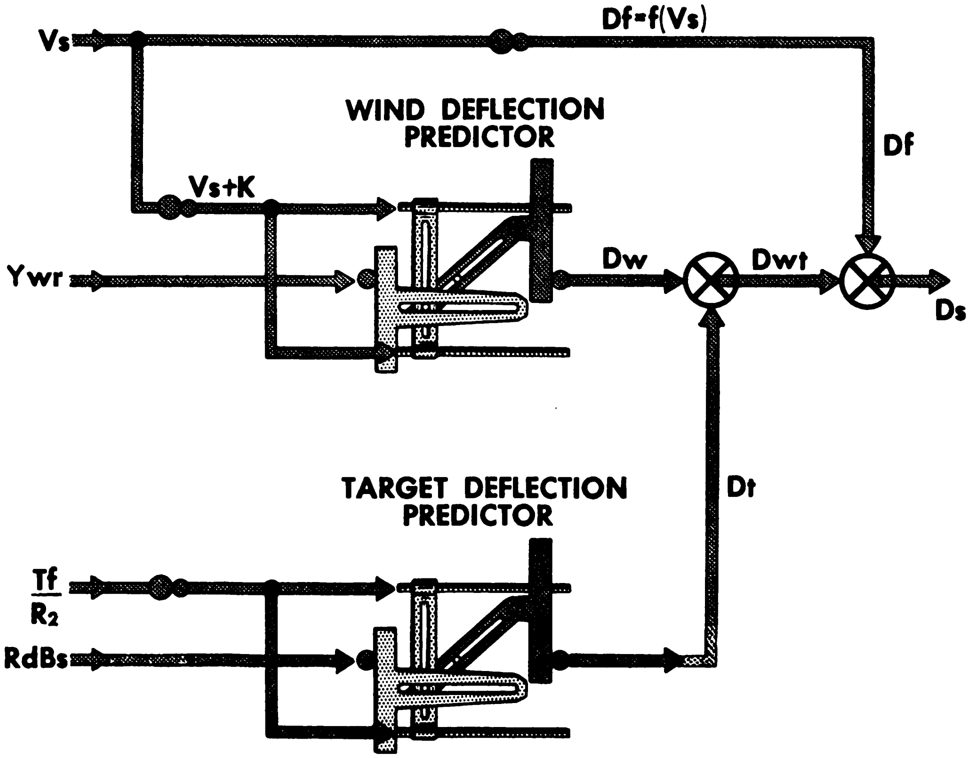


Figure 7-31.—Solving for sight deflection Ds.

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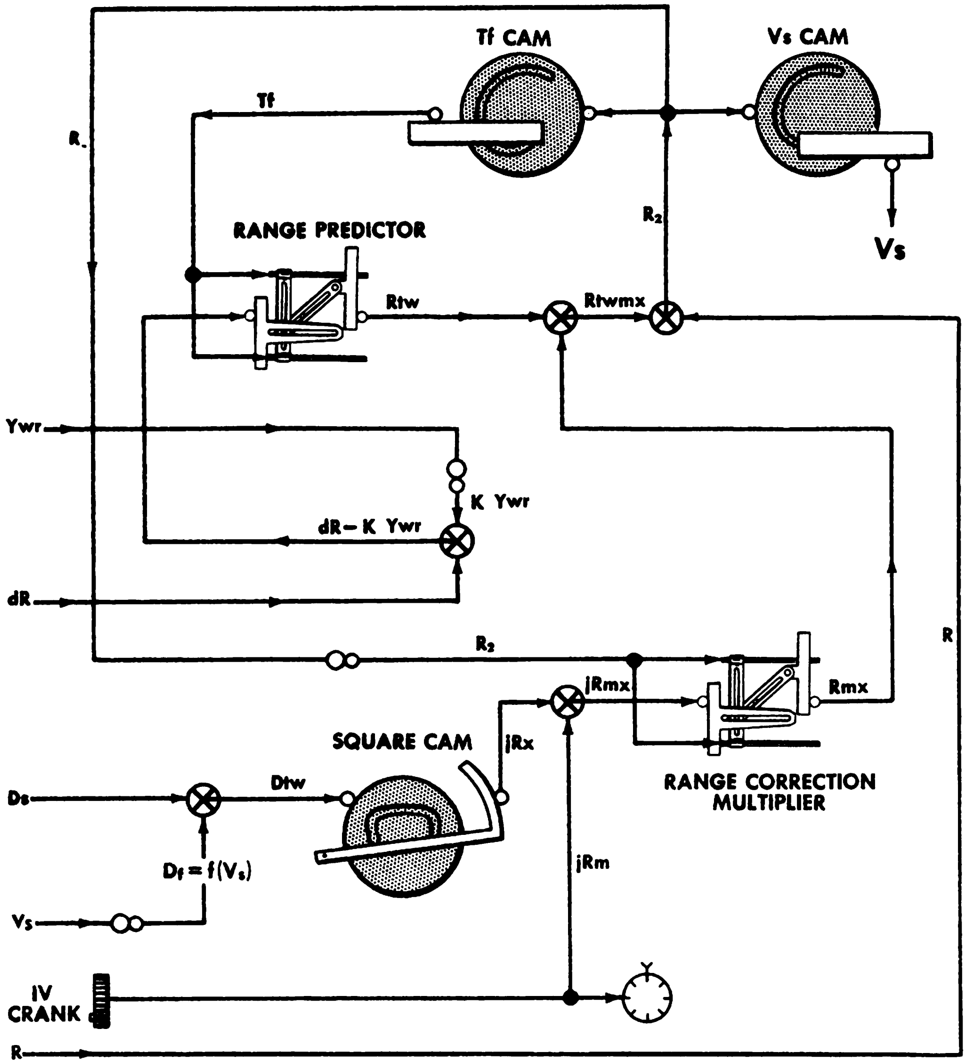


Figure 7-32.—Solving for sight angle Vs.

55.159

includes all the component sections you studied in figures 7-21, 7-27, and 7-30 of this chapter.

The key to solving Vs lies in how accurately R2 is computed. If R2 is correct, then Vs is correct, since Vs is taken from a cam positioned by R2. With all its corrections, R2 is corrected for wind, own ship and target motion, error due to deflection, and I.V. Thus you can say mathematically that

$$R2 = Rt + Rw + Rm + Rx + R.$$

However, only R exists separately in actual machines because each multiplier computes two things simultaneously. For example, the range predictor multiplier in figure 7-32 solves Rw and Rt together—with the inputs dR, Ywr, and Tf—to produce Rtw. And the range correction multiplier computes Rx and Rm together—with the inputs Ds, I.V., and R2—to give Rmx. Then Rtw and Rmx are added in a differential to give TOTAL RANGE PREDICTION, Rtwmx.

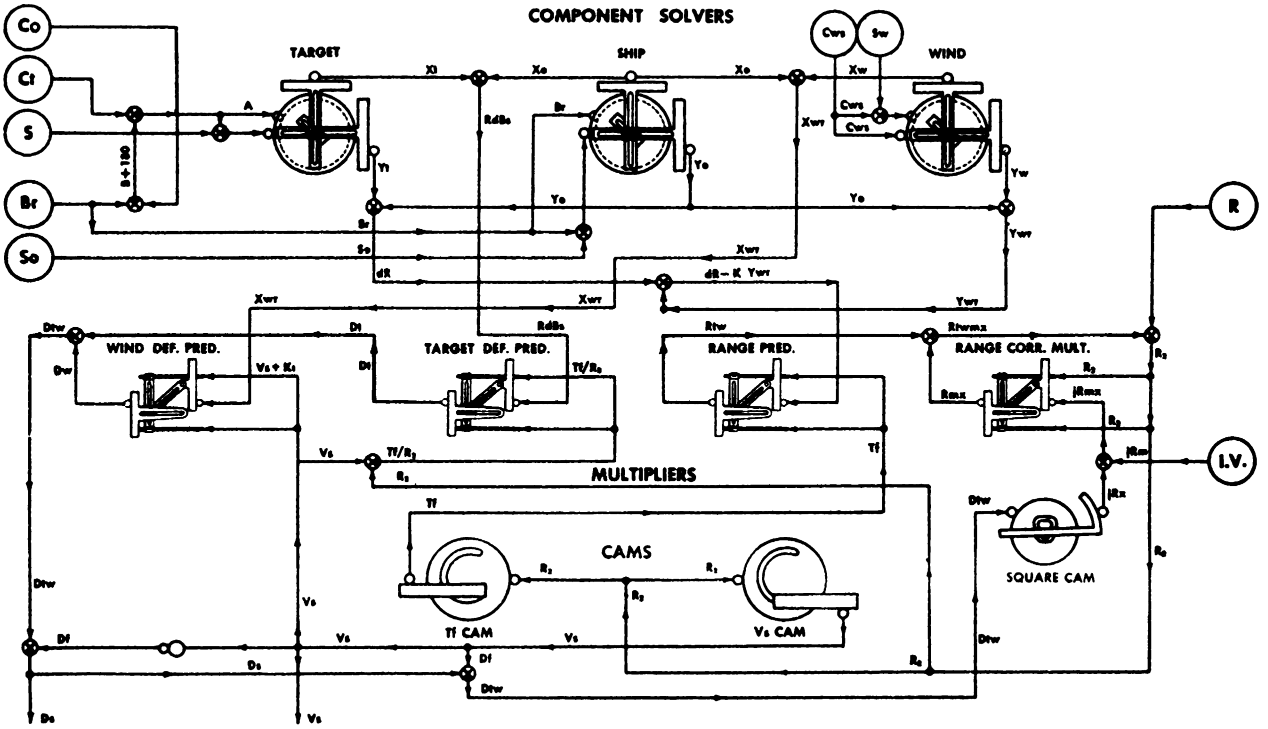
Finally, the total range prediction, Rtwmx, is added to present range R in another differential to give advance range R2.

You can see from the figure that you're again dealing with that ever-puzzling but useful "vicious circle." Several functions of R2 are fed back to the inputs to make up corrections in R2: A study of the diagram tells you that Tf, made from R2, helps make up Rtw; and that R2 and Vs (also made from R2), are fed back to enter into the solution of Rmx. It's therefore easy to see that the entire R2 computer is a regenerative affair. As you work with fire control instruments you'll learn to accept regenerative devices as ordinary gear.

There is one other thing in figure 7-32 that is no doubt puzzling you. That is, it doesn't look right to have both Ds and Vs as inputs when what you are solving is Vs. This is necessary because Df is made up as a function of Vs. And as you learned in figure 7-27, the partial range correction for deflection, jRx, was made by squaring Dtw. Since Ds contains Dtw (remember Ds = Dtw + Df), all you have to do to get Dtw is subtract Df from Ds in a differential as indicated in figure 7-32.

Now that you've completed your study of Vs and Ds ask yourself, do you really KNOW Vs and Ds? You are not expected to have memorized how Vs and Ds are computed, but you SHOULD be able to trace a blueprint of a surface rangekeeper to see how these two quantities are made up. And here's a test which will tell you whether or not you can: On figure 7-33 trace out the entire print.

The best way to trace out any schematic diagram is to start with the inputs, and then work on through the print to the ouputs taking one quantity at a time. The inputs in figure 7-33 are shown in circles. You'll notice that most of the constants that were mentioned as each section was discussed in detail are left out. Most constants that are not important to adjustment information are purposely left out in actual prints, so right now is a good time to get accustomed to working without them. However, if you need more detailed information about figure 7-33, go to the index and find out where the section you're in doubt about is located, and study it carefully.



55.160

Figure 7-33.—Simplified ballistic computer similar to those used in surface rangekeepers.

CHAPTER 8

SOLVING FOR WIND

Standard conditions as stated in the range tables assumed that there is no wind. Errors introduced by wind, and their corrections, are covered in the FT3 course. This chapter will consider how the wind effects a trajectory, and will show a typical wind problem solution.

Wind is the movement of air, and should not be confused with the resistance of air to a projectile passing through it. Wind is a force capable of doing work. The direction of the wind force is stated as the angle FROM which the wind is blowing. The wind tends to carry an object in the direction TOWARD which the wind is blowing. The effect that wind has on a projectile's trajectory depends on:

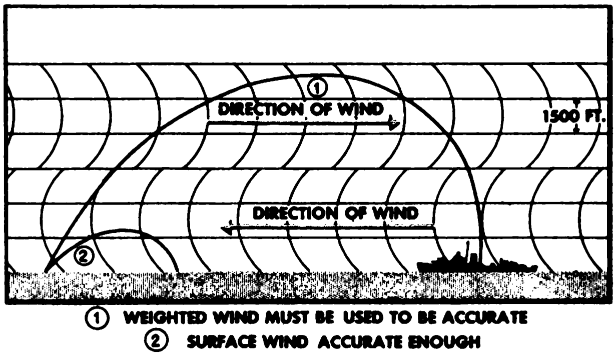
1. The strength of the wind force.
2. The surface area the wind is working on.
3. The resistance of the projectile to the wind force.
4. The length of time the wind acts on the projectile.

WINDS AT VARIOUS ALTITUDES

The strength of the wind is the intensity of the air's motion. The intensity depends on both the density of the air and its velocity. The density of the air varies at different altitudes. The velocity and direction may also vary at different altitudes. For instance, the wind might be blowing from the north on the surface of the ocean, and from the south at some higher level. You can see a typical situation in figure 8-1.

BALLISTIC WIND

If there's an aerological party aboard, an investigation of wind conditions at different elevations is made either by aloft observations from an airplane, or by observing the movements of a small balloon. The balloon's course is plotted as it proceeds upward through the 1500-foot bands shown in figure 8-1 so that wind direction and speed at each level may be evaluated.


①
DIRECTION OF WIND
1500 FT.
DIRECTION OF WIND
②
① WEIGHTED WIND MUST BE USED TO BE ACCURATE
② SURFACE WIND ACCURATE ENOUGH

55.161
Figure 8-1.—Winds at various altitudes.

After the wind at various levels has been weighted (corrected for air-density changes), a resultant or BALLISTIC WIND is calculated by the method set forth in figure 8-2. A plot of the weighted winds is drawn to scale, and the overall wind angle (Bw) and wind speed (Sw) determined. Bw is measured in degrees, and Sw is measured in knots. These values are then set into the computer to enter into the computations of gun orders.

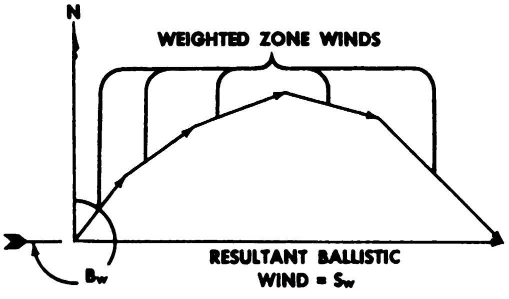


Figure 8-2.—Ballistic wind. 55.162

If aloft observations are not possible, the wind must be observed at the earth's surface. The use of surface wind direction and speed is not as accurate as ballistic wind values, but is often necessary. Frequently we do not have the time nor the facilities to compute a ballistic wind.

The wind force acts on the entire surface area presented to it. The effect of the wind on a projectile's trajectory is proportional to the projectile's surface area acted on by the wind. The surface area (shape) of a projectile is a designed feature; it is considered in the wind problem as a modifying factor in the formulas.

The resistance of a projectile to the wind force is proportional to the projectile's momentum. To get an idea of the significance of momentum, look at the curves for three representative projectiles in the graph of figure 8-3. These curves show the lateral deflection of the projectile in yards for a crosswind at 10 knots. For example, at a range of 10,000 yards the 3''/50 projectile is deflected 135 yards. However, at the same range the 5''/38 projectile is deflected 55 yards and the 16''/45 projectile less than 10 yards.

The difference in the curves is caused by the difference in the momentum of the projectiles. Momentum is equal to the product of mass and velocity. The larger projectiles has more momentum and can resist the effects of wind more than small projectiles can.

The length of time the wind force acts on a projectile also affects the total amount of deflection. The time the wind force acts on a projectile is the time of flight (Tf)—the time it takes for the projectile to reach the target.

It is interesting to notice that the wind deflects the projectile more and more as range increases. When the shell is first fired, it is traveling so fast that the wind has little chance to affect it. But as the projectile starts losing speed the wind begins to deflect it to a marked degree. That is why the curves in the graph (fig. 8-3) sweep upward as the ranges increase. Obviously, the effect of wind varies as a function of range, rather than directly with range.

We will cover the surface wind problem in this chapter. Later in another chapter of this text we will cover the AA wind problem. In both problems the effect of the wind is to change both the angle of departure and the average velocity of the projectile with respect to still air.

You will recall from the preceding chapter that the rangekeeper resolves both true wind and own ship's wind into components in and across the line of sight (LOS). In this chapter we will cover the true wind problem. Own ship's wind is covered with the relative motion problem.

CROSSWIND

Every ship at sea is influenced by wind blowing from some direction of the compass. Except during a hurricane or some other unusual disturbance, this is always a single wind. However, regardless of where the wind is blowing from, the important thing is the angle it makes with the line of fire (LOF). It is easy to realize that if the wind is blowing directly across the LOF it will deflect the projectile to left or right, and if the wind is blowing along the LOF it will speed up or slow down the projectile. But the wind is rarely so accommodating as to blow directly across or along the LOF—instead, it usually blows at some other angle.

Even so, it is necessary to figure out how much the wind will affect the RANGE and DEFLECTION of the projectile, and apply the necesary corrections to the gun position. It is obviously much easier to take a single wind and think of it as two component winds, one blowing across, and the other along, the LOF. Then you can take the crosswind component and compensate for it by a correction to sight deflection (Ds); and take the range wind component (component blowing along LOF) and compensate for it by a correction to sight angle (Vs).

This explains why, in actual practice, wind blowing at AN ANGLE to the LOF is resolved into components along and across the LOF, and is corrected for as though you were dealing with two individual winds.

Let's study the two wind components separately. Crosswind is considered separately from drift, and is added to sight deflection as an individual correction. To get an idea of the effects of crosswind on a trajectory, take another look at the curves in the graph of figure 8-3. You will recall that distance is equal to speed multiplied by time. And so your first thought is that the total deflection of the projectile will be equal to Tf x Sw. You would be on the right track, but a little incorrect because the projectile won't deflect at the same speed that the wind is blowing.

The equation can be modified and made more nearly correct by multiplying by a small constant (k) whose value is dependent on the shape

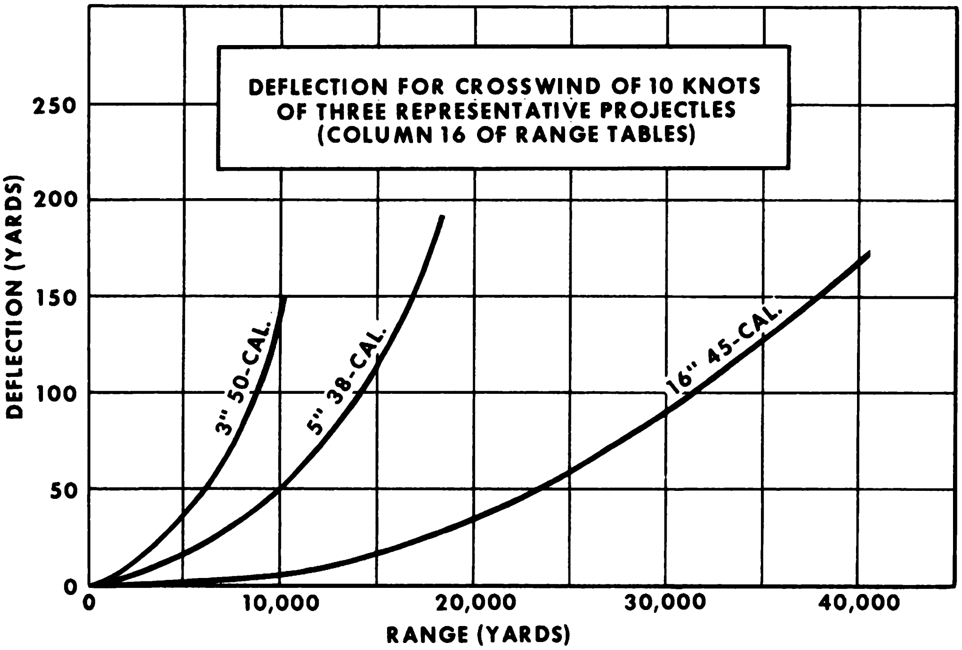


Figure 8-3.—Crosswind curves.

55.163

and weight of the shell. Now you can say that the total deflection distance, as a result of crosswind, will be

k x Tf x Sw.

This formula is not satisfactory unless you modify it a bit more. First, you want to convert it to yards deflection at the target. Since Sw is in knots, you multiply it by 0.563 to convert it to yards per second. Then: Sw x 0.563 = yards/seconds.

Next, to get the distance deflection in yards (linear deflection), you multiply Sw by time (in this case, Tf). Now you have

linear deflection due to wind =
k (Tf x Sw x 0.563) yards.

This last formula gives you the yards deflection at the target, but before it can be used to correct sight deflection (Ds), it must be converted to angular measure, or mils. Simply divide yards deflection by range.

The angular deflection due to wind—ANGULAR WIND DEFLECTION (Dw)—now becomes

$$Dw = \frac{k \times Tf \times Sw \times 0.563}{\text{Adv. Range}}.$$

Notice that you use ADVANCE RANGE (R2), the range to the future target position.

Let's stop right here and see what can be done to solve the equation for DW by the use of the basic mechanisms. Looking over the equation you will immediately decide that the two constants—k and 0.563—can be handled by gear ratios. Also, you may decide to multiply Tf and Sw in a multiplier. So far, so good. But now you still have to divide by R2. You scratch your head a moment, and come up with an answer requiring a reciprocal cam and another multiplier. That gives you a setup like the one in figure 8-4.

This arrangement would work fine, but it would be entirely too bulky and expensive. In order to cut down on the number of computing units, rangekeepers sometimes use a Tf/R2 cam which is a combination of the reciprocal cam and Tf cam. This eliminates the use of one multiplier, and gives you the setup shown in figure 8-5.

R2 rotates the Tf/R2 cam; Tf/R2 is taken from the cam follower to position the input rack of a screw type multiplier.

Sw (in this case, the crosswind speed in knots) is multiplied by k in a gear reduction, and it positions the screws and input slide of the multiplier.

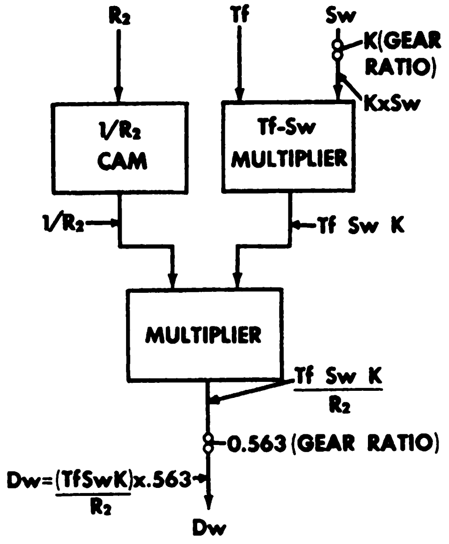


Figure 8-4.—Solving Dw. 55.164

The position of the output rack is proportional to the product Tf/R2 x Sw x k, which is then multiplied in another gear reduction by 0.563 to give you Dw in mils.

Since all ballistics are functions of advance range and advance elevation (range and elevation of future target position), many shortcuts are performed to eliminate the use of extra gear. The object is to use the minimum of parts. For instance, rather than computing Tf/R2 in a cam, it is usually made from other quantities which already exist in the machine. This of course would further simplify the Dw computer in figure 8-5. You will see many of these arrangements when you study the actual equipment.

EFFECT OF RANGE WIND

The corrections for range wind are similar to those for crosswind, and are solved in much the same way. Range wind blows parallel to the LOF, either with or against the motion of the projectile, and gives it a forward or backward velocity that is independent of other motions. This velocity will equal k x Sw, and will be moving the projectile throughout the time (Tf). The value of k, of course, will not be the same at a particular range as for crosswind, because the wind will be acting on different surfaces of the projectile.

Here again, the computation for a 10-knot range wind has been performed for you in the range table. When plotted, these values will give you a set of curves similar to those for crosswind in figure 8-3.

Unlike crosswind, corrections for range wind are applied to advance range, as the name might imply. Therefore, the correction would be measured in yards rather than in mils. Fortunately, this simplifies the computations because you have only to multiply by 0.563. It is not necessary to divide by advance range as you must to determine crosswind.

The correction for range wind then becomes

k x Sw x Tf x 0.563 yards.

But, as with crosswind, k varies with range. The range wind correction is added to R2 in Df2, completing the process of range correction for wind (fig. 8-6).

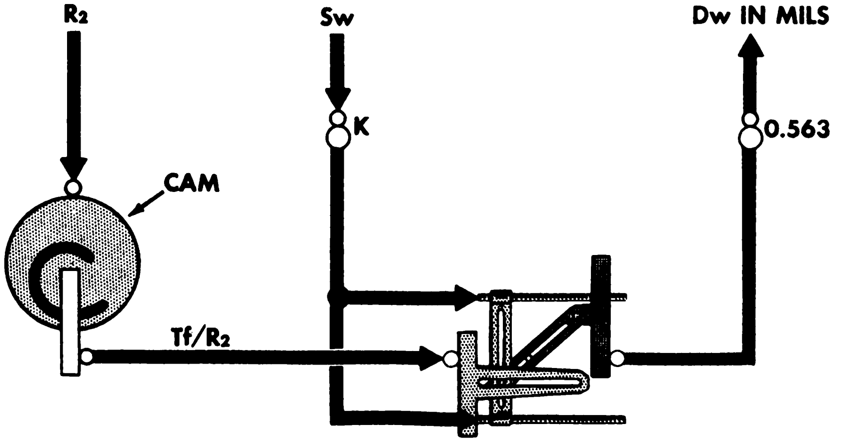


Figure 8-5.—Solving Dw with a cam and multiplier. 55.165

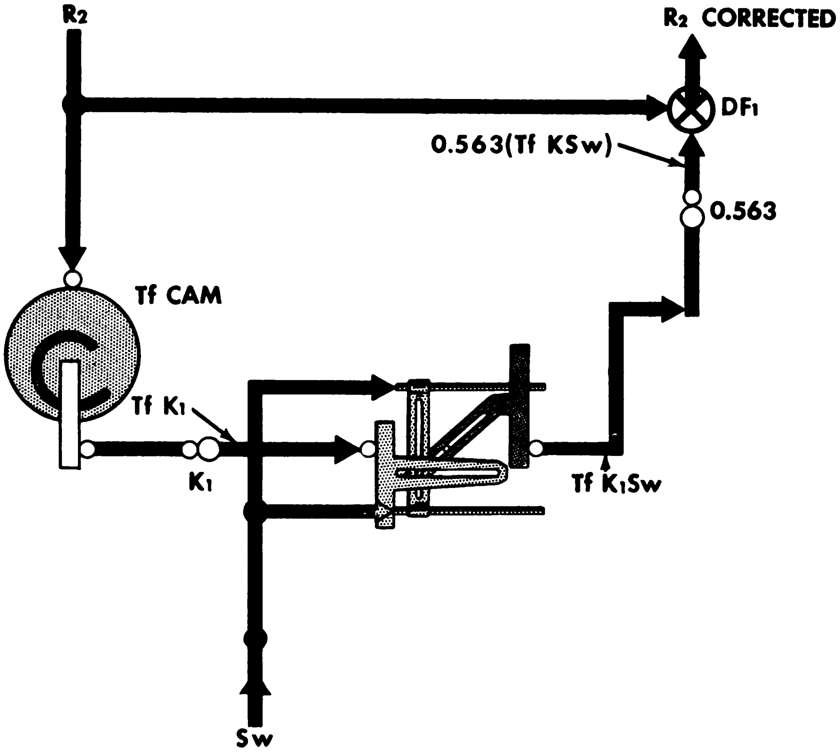


Figure 8-6.—Computing range wind correction. 55.166

WIND AT AN ANGLE

Up to now you've learned about corrections for wind blowing directly across and along the LOF. It is seldom, however, that wind will be so accommodating as to limit itself to these directions. Instead, it generally comes from a direction that makes an oblique angle with the LOF.

Before you can study winds at such an angle, it's necessary to define a few angles.

Customarily, you always describe a wind by indicating the direction it is coming FROM. An east wind is blowing FROM the east, toward the west. For this reason the direction of the wind is always measured from north in a clockwise direction to the direction from which the wind is coming.

Figure 8-7 shows two wind angles. The first is Bw (TRUE WIND DIRECTION). This is the value of wind you set up on the dials of a rangekeeper.

Bw is not used as it stands in solving the fire control problem. Instead Bw is converted to a quantity known as WIND COURSE (Cw). Cw is measured from north to the direction toward which the wind is blowing, as indicated. A study of the figure will tell you that

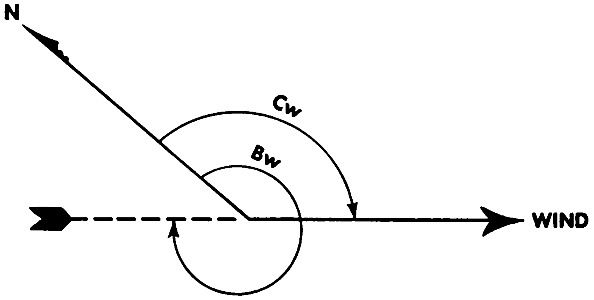


Figure 8-7.—Wind angles Bw and Cw. 55.167

$$Cw = Bw - 180$$

or,

$$Cw = Bw + 180.$$

The whole idea of the wind problem is to take a wind of known direction and speed and resolve it into components in and across the LOS. Then you take these components and proceed as you did with range wind and crosswind.

Notice that you use the LOS rather than the LOF. For true accuracy you should use the LOF, but since Ds is comparatively small in surface fire control, the LOS makes a good enough reference. However, for fast-moving air targets, Ds is so large that it is necessary to use the LOF.

The angle the wind makes with the LOS is called Cws (standing for wind course relative to the LOS), shown in figure 8-8. It is measured from the arrowhead of the wind vector clockwise to the LOS. To obtain this angle you must know the true bearing of the LOS, so you use true target bearing (B) which is measured from north clockwise to the LOS.

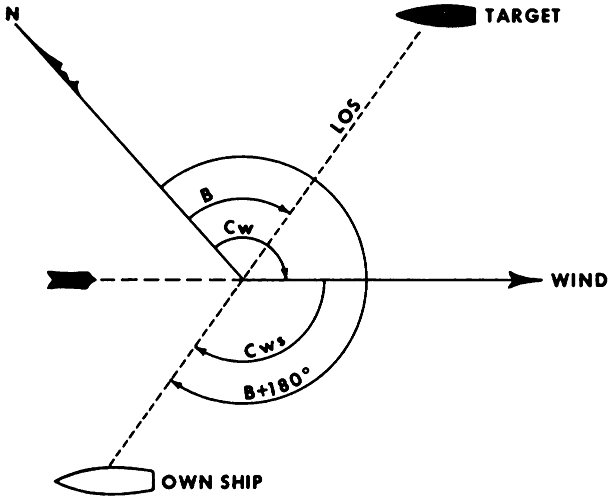


Figure 8-8.—Wind course measured relative to the LOS. 55.168

However, there's another hitch. B isn't measured directly, but instead, is made up from Br and Co. Br is measured by the director, and Co is received automatically from the master-gyro compass; they can also be cranked in manually by handcranks. As shown in figure 8-9, B is equal to

$$B = Br + Co.$$

Now that you have the true bearing of the LOS, you're ready to find Cws. It is computed from B and Cw as shown in figure 8-9. A study of the figure will tell you that

$$Cws = (B + 180) - Cw.$$

Cws can be solved in the rangekeeper with a couple of differentials as shown in figure 8-10.

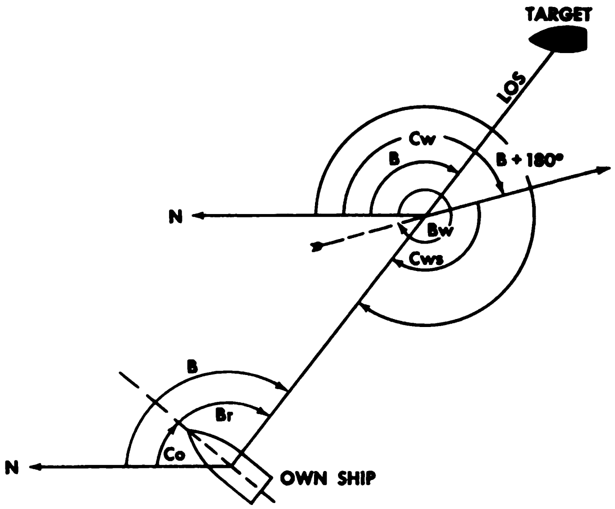


Figure 8-9.—How Cws is obtained. 55.169

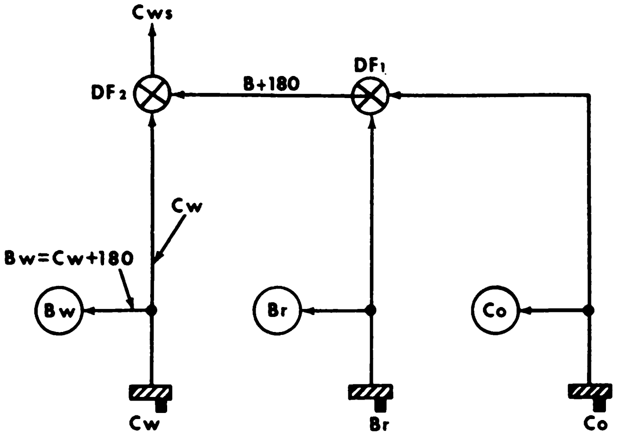


Figure 8-10.—How Cws is computed mechanically. 55.170

Co and Br are added in DF1 to give B; and (B + 180) and Cw are subtracted in DF2 to give Cws in degrees. The 180 constant is put in by slipping the shaft connecting DF1 and DF2 by 180 degrees.

RESOLVING THE WIND VECTOR

So far you know these things about the wind vector: first, you know its direction (Cws) with respect to the LOS; second, you know its speed (Sw). That gives you the setup in figure 8-11. Also, you know that wind has two effects—the effect of pushing the projectile sidewise, and that of shortening or lengthening range. So you resolve the vector into its two right-angle components, Xw and Yw. Xw is the crosswind component, and Yw is the range wind component.

From your knowledge of trigonometry you know that these components added will have the same effect as the single vector (Sw).

That leaves only the problem of breaking down Sw into its components with the component solver. To calculate the values of the components, notice that

$$Xw = Sw \times \sin Cws$$

$$Yw = Sw \times \cos Cws.$$

For the case shown in figure 8-11, remember that the trigonometric functions of Cws are the same as those for angle a except for its numerical sign, because a is the supplement of Cws. Angle a equals 180° - Cws.

Actually, in the wind problem you don't have to worry about the sign of trigonometric functions, because the component solver automatically comes up with the correct sign.

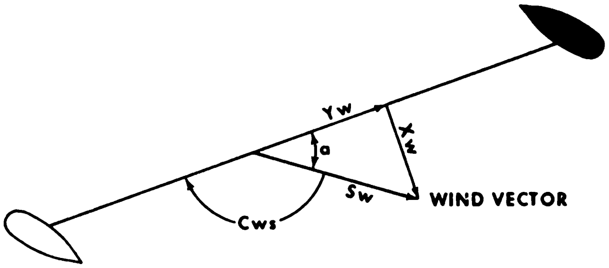


Figure 8-11.—The wind vector. 55.171

Figure 8-12 shows how the component solver breaks down Sw. Cws is the input to the angle gear, and Sw is the input to the speed gear. Then Xw and Yw are the slide outputs.

SIMPLIFIED MECHANICAL WIND COMPUTER

How would you like to sum this whole chapter up in one diagram? Figure 8-13 does just that. It takes the wind vector, resolves it into the Xw and Yw components, and solves for crosswind and range wind corrections. This setup is one similar to those used in rangekeepers controlling surface fire.

First, notice the formation of the inputs to the wind component solver. Wind speed Sw is inserted by rotating the wind-speed crank until the proper value shows up on the Sw dial. Br and Co are shown as being put in by handcranks. You know, of course, that these values come in automatically. Then Br and Co are combined in DF1 to give B.

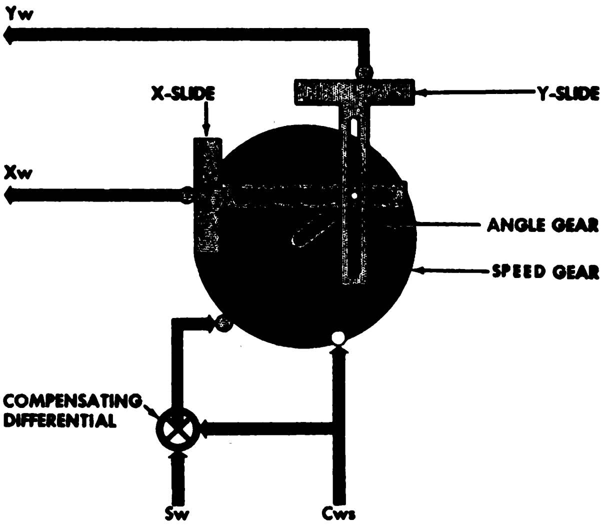


Figure 8-12.—Resolving the wind vector with a component solver. 55.172

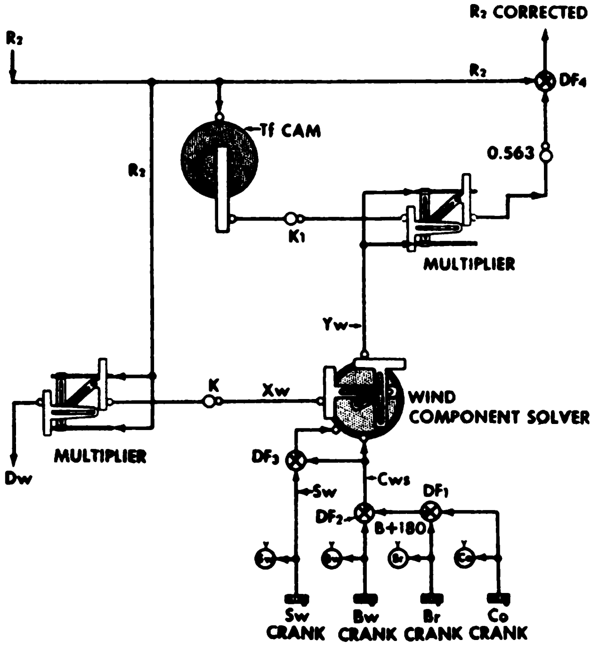


Figure 8-13.—Example of a device to compute wind correction. 55.173

The wind-direction crank actually puts Cw into the hookup, but the indicating dial is connected up 180° out, so it reads wind bearing (Bw).

Cw is combined with B in DF2 to give Cws.

This is the angle input to the wind component solver. Cws is constantly changing as the target moves, but with this setup you need to introduce wind values only once. Then, if correct values of Br and Co are maintained, the correct value of Cws will always show up on the component-solver input.

DF3 is the compensating differential which is found in every component solver. You will recall that it prevents the length of the vector from changing when the angle changes.

Deflection correction due to Xw is solved exactly the same as shown back in figure 8-5 except that Xw is substituted for Sw. Range correction due to Yw is solved the same as it was back in figure 8-6, except that Sw is again substituted for, but this time by Yw.

Follow through the computation for range wind and crosswind in figure 8-13, and review the computations step by step. The range component (Yw) of the wind vector (Sw) is fed into the upper multiplier. The other input to the multiplier is Tf, which is obtained from a cam and multiplied by the constant (K1) in a gear ratio before positioning the slide input. The result is the correction for advance range to compensate for range wind, and is combined with advance range at DF4.

Mils deflection due to wind is obtained by the approximate formula, K x Xw x R2. R2 and the Xw component of the wind vector are the inputs to a multiplier. The output is deflection due to wind, Dw.

This completes the study on wind corrections. It has told you about wind, but, just as important, is has shown you how computing units like multipliers, differentials, and component solvers work together.

CHAPTER 9

DECK AND TRUNNION TILT

In chapter 7 of this course, we solved the fire control problem with respect to the horizontal plane, and used the earth frame of reference. You will recall that a system using the earth frame is either fully or partially stabilized. Due to the limitations placed on a system installed aboard ship, a fully stabilized system is not always practicable. You will find that most systems are only partially stabilized. In a partially stabilized system, the information furnished the computer from the director is measured with respect to the deck plane. This is because directors are mounted with their roller paths parallel to the deck plane, and their movement is measured with respect to the deck plane. The same thing is true at the opposite end of the problem. Gun mounts and weapon launchers are also mounted with their roller paths parallel to the deck plane. It follows that the orders transmitted from the computer must also be measured with respect to the deck plane.

To simplify the explanation of the problem, we assumed in chapter 7 that the deck and horizontal planes were one and the same. After a short time aboard ship in a storm, you know for sure that this is not true. It doesn't take long to realize that the deck plane repeatedly moves out of the horizontal plane by the amount of own ship's roll and pitch. Since the deck plane deviates from the horizontal plane, some means must be found to measure this discrepancy and correct for it.

Corrections for deck inclination are resolved into components in planes IN and ACROSS the line of sight. The component in the line of sight is called level; the component across the line of sight is called crosslevel. The primary method of measuring level and crosslevel is with a stable element or a stable vertical, which is essentially a gyroscope with suitable servosystems. Although the stable element and the stable vertical are quite similar, only the stable vertical, in association with the surface problem, will be discussed in this chapter. We will consider the stable element in a later chapter, when we cover the air problem.

The stable vertical furnishes level and crosslevel for the DECK TILT and TRUNNION TILT sections of the rangekeeper. The deck tilt section's output is used to establish a horizontal plane in the rangekeeper for the computation of all ballistic corrections. The trunnion tilt section's outputs are used to modify the gun train and elevation orders to compensate for the tilt of the gun trunnions.

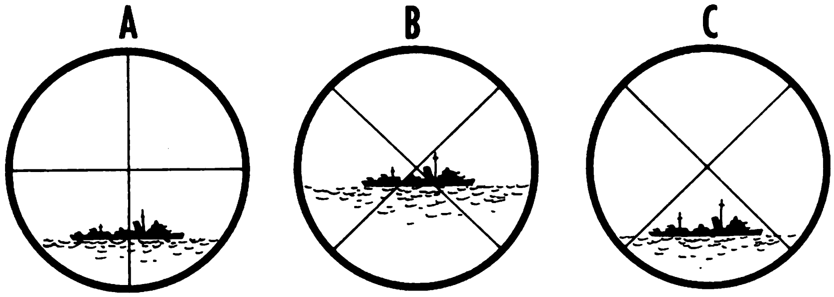
LEVEL AND CROSSLEVEL

The director tilts with the deck as own ship rolls and pitches. If you were a director pointer or trainer sighting on a target, and there were no corrections for own ship's roll and pitch, the target would appear to move with respect to the telescope crosswire as indicated in figure 9-1. If the ship were tilted in the vertical plane containing the line of sight (LOS), the target would appear to move above or below the horizontal crosswire as indicated in figure 9-1A. The angle by which the crosswire intersection is displaced vertically from the target is called the LEVEL ANGLE.

If the ship were tilted in the vertical plane across the LOS as shown in figure 9-1B, the crosswires would remain on target, but they would rotate around the LOS. The angle, measured in the vertical plane ACROSS the LOS, made by the horizontal crosswire and the horizontal, is called CROSSLEVEL.

With both level and crosslevel present, you would see the target through the crosswires as shown in figure 9-1C. Notice that the telescope crosswires are displaced vertically as a result of level, and rotated around the LOS as a result of crosslevel.

Like all other computations we have made so far, the LOS is the reference line for measuring level and crosslevel. As shown in figure 9-2, the level angle is measured in a VERTICAL



EFFECT OF LEVEL

EFFECT OF CROSSLEVEL

TOTAL EFFECT

Figure 9-1.—What the pointer and trainer observe through their telescopes. 55.174

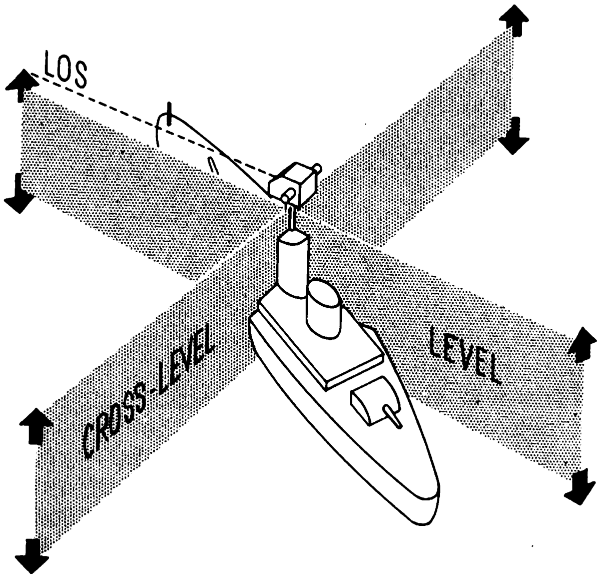


Figure 9-2.—The level and crosslevel angles are measured in respect to the LOS in vertical planes indicated by the arrows. 12.46

PLANE CONTAINING THE LOS. The crosslevel angle is measured in a VERTICAL PLANE AT RIGHT ANGLES TO THE LOS.

The effects of level and crosslevel can best be seen by the use of spherical diagrams. The drawing in figure 9-3 is a basic spherical diagram. The ship is located in the center of the sphere. The true vertical passes through the fire control system's reference point. In this diagram the deck plane coincides with the horizontal plane, and neither level nor crosslevel is present. Notice that the director LOS is positioned through the angle, Br (relative target bearing), from plane E to plane A.

If the ship's deck is tilted, as shown in figure 9-4, so that all the tilt is in the plane containing the LOS, only level L' is present. You can see that L' would displace the LOS to a point below the horizontal as shown by the dotted line in figure 9-4. A tilt of the ship's deck in the opposite direction would move the LOS above the horizontal. Look at it this way: The LOS must be elevated to compensate for level when the deck is tilted as shown in figure 9-4; but if the deck is tilted in the opposite direction, the LOS must be depressed to correct for level.

Now imagine that the deck of the ship is tilted across the LOS as shown in figure 9-5. The angle that plane D makes with plane A is CROSSLEVEL (Zh). Notice that Zh has no tendency to displace the LOS in the absence of L'.

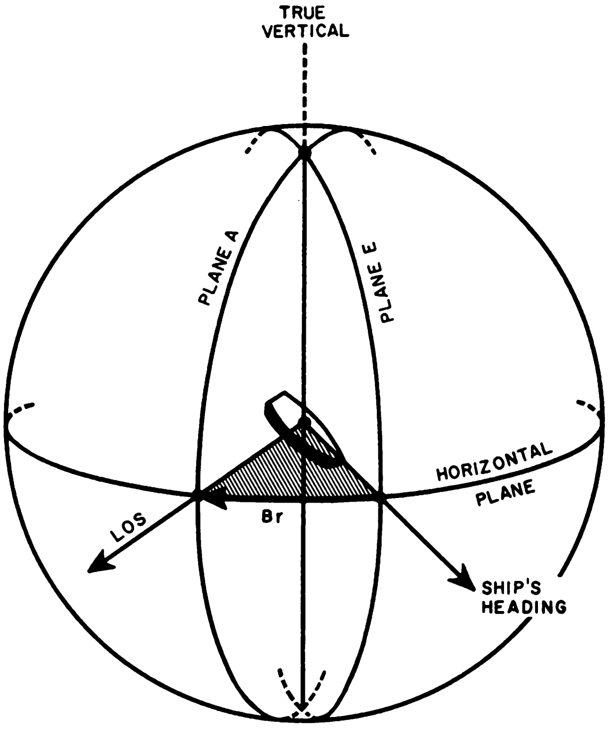
Figure 9-6 shows what happens when both level and crosslevel are present. A study of the diagram shows that if no corrections were made, the LOS would be displaced below the horizontal plane as indicated by the dotted line. Also, notice that the relative bearing measured by the director (B'r') in the deck plane would not be the same angle as the relative bearing in the horizontal plane (Br).

Summing it up, the roll and pitch of the ship introduce errors caused by the movement of the deck plane out of the horizontal plane. The stable vertical measures the movement of the deck plane with respect to the LOS and transmits the corrections, L' (level) and Zh (crosslevel), to the rangekeeper to enter into the computation.

The question might arise, "Why use the horizontal plane to solve the fire control problem?"

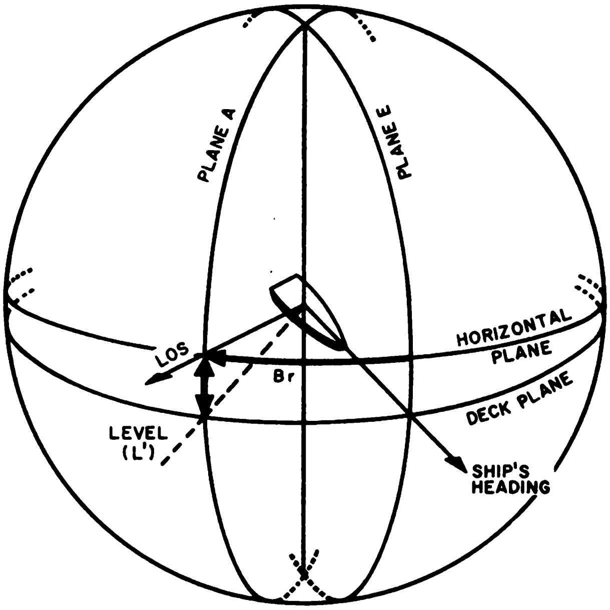
The answer is this: The geometry of the solution of the prediction problem is a simple matter of multiplying the target's rates and the time of flight. However, the job of determining properly smoothed target rates is one of the most difficult problems confronting a fire control system. The computer solves the fire control problem with a degree of refinement consistent with the accuracy and smoothness of the information furnished it. The use of the horizontal plane in the computer eliminates the changes in the quantities due to the tilting of own ship's deck. Consequently, the rates established in the computer consist only of the relative motion between own ship and the target. Therefore the accuracy and smoothness of the solution is greatly improved.

Before leaving this section, be sure you understand that L' is measured in a vertical plane containing the LOS, and Zh is measured in a vertical plane across the LOS. Otherwise a thorough understanding of what the stable vertical does will be difficult.



PLANE A VERTICAL PLANE CONTAINING LOS
PLANE E VERTICAL PLANE THROUGH CENTERLINE OF SHIP

Figure 9-3.—When the deck is level (coincides with the horizontal plane as shown), no level or crosslevel is present. 55.175



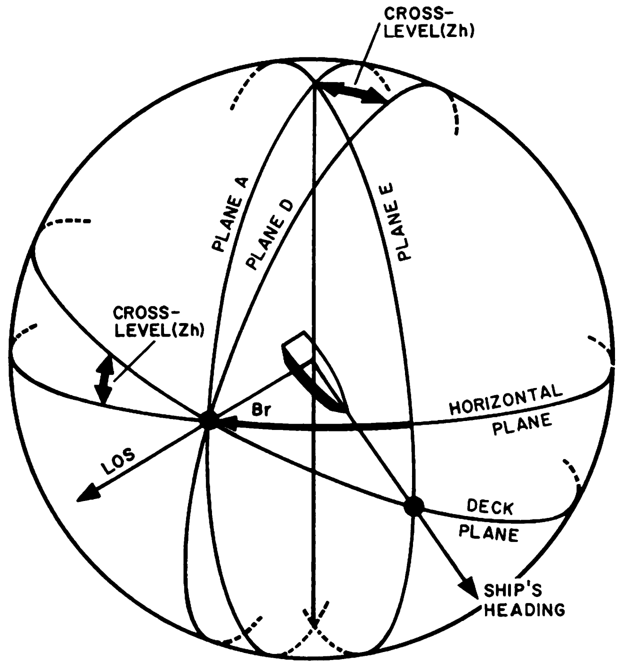
PLANE A VERTICAL PLANE CONTAINING LOS
PLANE E VERTICAL PLANE THROUGH CENTERLINE OF SHIP

Figure 9-4.—When the deck is tilted as shown, only level is present. 55.176

STABLE VERTICAL

The stable vertical consists primarily of a high speed gyro with its spin axis in the vertical plane. The spin axis is maintained in the vertical plane by two precessional devices: the latitude correction weight and the gimbal rotation-righting force. Thus the axis of spin of the gyro is in a vertical plane related to the earth, rather than fixed in space as is characteristic of a free gyro. The gyro wheel will therefore be in the horizontal plane at all times, and the ship appears to tilt about the gyro. Consequently, the stable vertical provides an excellent means of measuring level and crosslevel.

You can get an idea of how the stable vertical does its job in figures 9-7 and 9-8. The gyro is mounted in gimbals which, except for the mounting, have no mechanical connections to other elements (fig. 9-8). Complete freedom of motion of the gyro system about two axes is obtained. The gyro's gimbal axes are always oriented so that one of them remains in the LOS and the other across the LOS. Therefore the tilt of the deck in the vertical plane containing the LOS as measured by the gyro will be level. It follows that the



PLANE A	VERTICAL PLANE CONTAINING LOS
PLANE D	PLANE PERPENDICULAR TO DECK PLANE CONTAINING LOS
PLANE E	VERTICAL PLAN THROUGH CENTERLINE OF SHIP

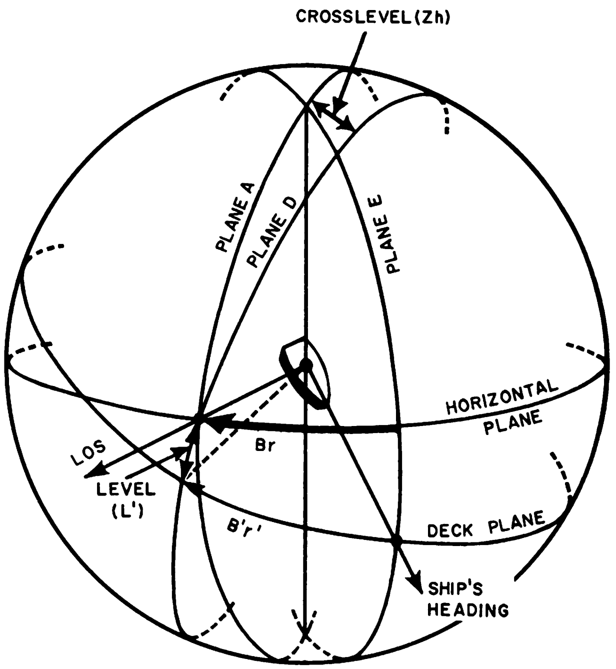
Figure 9-5.—When the deck is tilted around (across) the LOS, without displacing it vertically, as shown, only crosslevel is present. 55.177

tilt of the deck in the vertical plane across the LOS as measured by the gyro will be crosslevel.

The gyro gimbals are positioned relative to the LOS as shown in figure 9-7 by the input B'r'. Input B'r' is relative target bearing as measured by the director in the deck plane of the ship. This quantity is called director train.

Let's examine the stable vertical more closely. Figure 9-8 shows a simplified stable vertical placed outside of its case and mounted on a ship. The figure also shows the names of the various major parts. B'r' is received electrically from the director by synchro transmission and a servo followup motor. The servo (not shown) drives the training shaft.

On top of the gyro assembly is mounted a magnet which is energized by 115-volt alternating current. An umbrella (a set of electrical figure-eight coils—one for level and one for crosslevel) is mounted on the crosslevel gimbal as shown in figure 9-9.



PLANE A	VERTICAL PLANE CONTAINING LOS
PLANE D	PLANE PERPENDICULAR TO DECK PLANE CONTAINING LOS
PLANE E	VERTICAL PLANE THROUGH CENTERLINE OF SHIP

Figure 9-6.—When the deck is tilted across and in the LOS as shown here, both level and crosslevel are present. 55.178

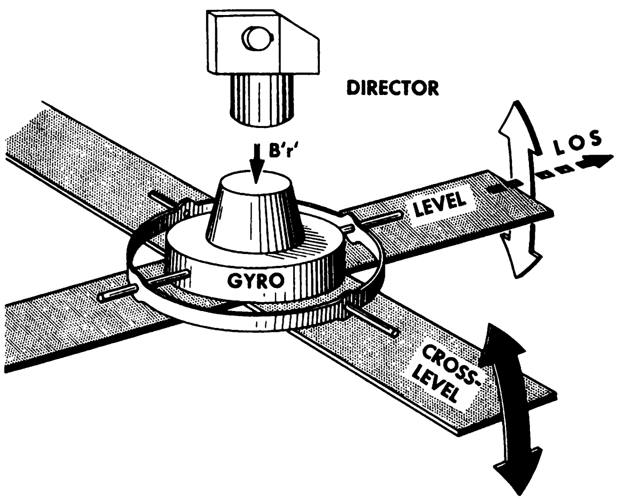


Figure 9-7.—The gyro measures level and crosslevel. 55.179

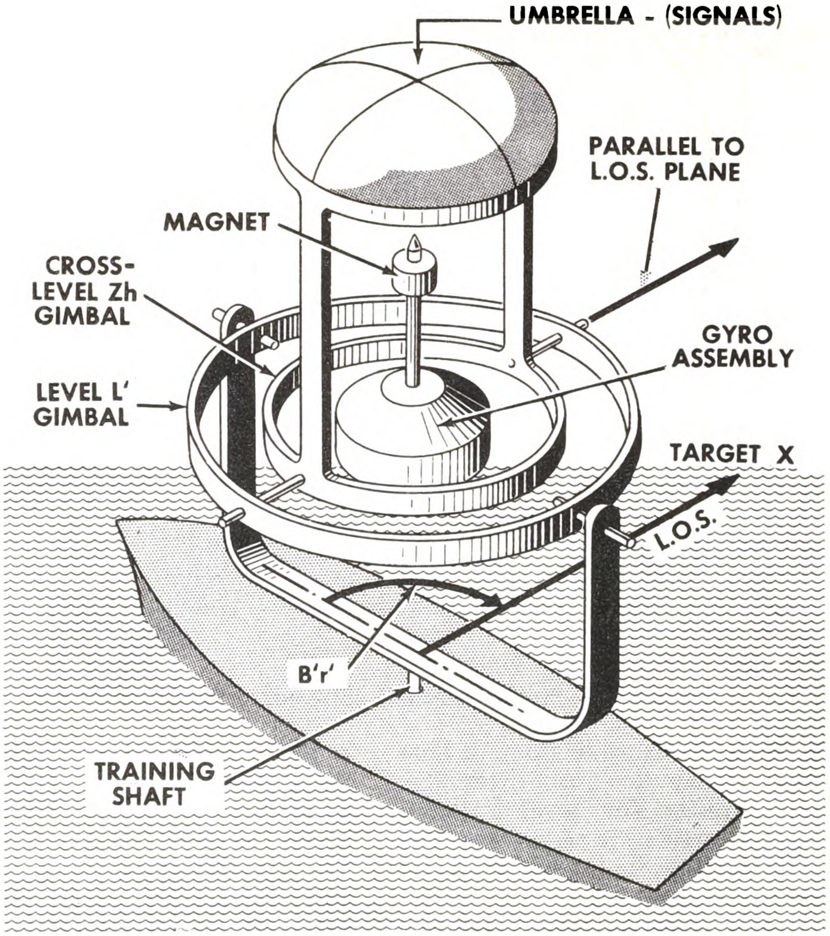


Figure 9-8.—Simplified stable vertical schematic diagram. 55.180

When the ship is perfectly stable (horizontal), the magnet points directly at the intersection of the lines on the umbrella. The voltages induced in the two figure-eight coils are equal and opposite. The signal output is therefore zero. But if the ship is tilted, the gimbal assembly and fork roll around the gyro, and the magnet points at some other point on the umbrella. This produces an output signal voltage in the umbrella coils. This voltage is then amplified and fed to a set of electric followup motors (one for level and one for crosslevel). The followup motors reposition the level and crosslevel gimbals so that the center of the umbrella is again over the magnet (fig. 9-9). In repositioning the umbrella, the followup motors have driven out the L' and Zh angles at their shafts.

This type of followup (servo) system is no stranger to you. The devices employed here were covered in chapter 3 of this course.

HOW THE STABLE VERTICAL MEASURES LEVEL

In figure 9-10 the deck has tilted so that all of the motion is about the level axis; that is, motion is about the pivots of the outer or level gimbal on the supporting fork. This displacement about the level axis is the LEVEL ERROR.

When the deck is inclined as shown in figure 9-10, the outer (level) gimbal initially moves with deck motion, and the umbrella moves with respect to the a-c magnet, which is maintained in the vertical by the gyro. An electrical signal is

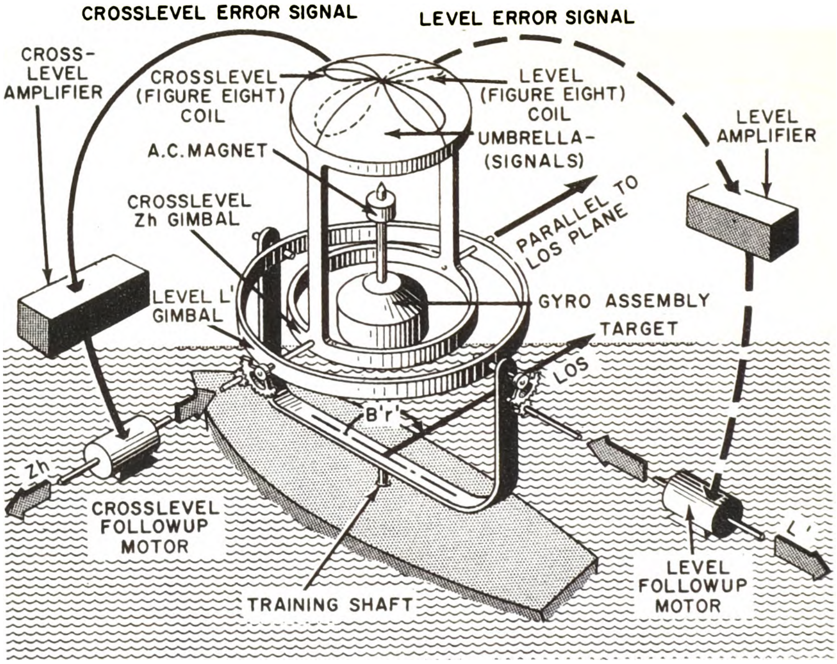


Figure 9-9.—Stable vertical followup control assembly.

55.181

now generated in the level figure-eight coil. This signal is amplified by the level amplifier (fig. 9-9) whose output excites the level followup motor. As the motor drives, it repositions the level gimbal so that the umbrella is again centered over the a-c magnet.

In figure 9-11 the instrument is pictured as it would look AFTER the level motor has restored the level gimbal to the horizontal. The motion of this gimbal is, therefore, a measure of L', which appears as a shaft position at the level followup motor.

Note that the level gimbal is mounted in the fork, which is in turn supported by the deck. Thus the level axis is always kept parallel to the deck by the level followup motor. The level angle is always measured in a plane containing the LOS and perpendicular to the deck. It should also be noted that by leveling the level gimbal the crosslevel pivots of the inner gimbal are brought back to the horizontal. As a result, the crosslevel axis is always kept horizontal as shown in figure 9-11.

HOW THE STABLE VERTICAL MEASURES CROSSLEVEL

Crosslevel is measured differently than level, because the crosslevel is defined in a vertical plane at right angles to the LOS. In figure 9-12 deck motion is all in crosslevel, that is, the ship is inclined so that the entire assembly is rotated about the crosslevel or Zh axis. Notice that the Zh axis always lies in a plane with the LOS, and even though the whole assembly is tilted about this axis, no tilt occurs about the level axis. Thus the umbrella in this case is displaced only by crosslevel.

When the umbrella receives the crosslevel motion, a voltage is induced in the cross-level figure-eight coils which controls the crosslevel followup motor shown in figure 9-9. This causes the motor to drive the crosslevel gimbal until the umbrella is again centered over the magnet, and the umbrella signal again falls to zero causing the motor to stop as shown in figure 9-13. In driving the crosslevel gimbal and umbrella back to the neutral position, the motor shaft also turns an amount proportional to Zh. And like L', Zh appears as a motor shaft position which is fed to the rangekeeper.

MEASURING L' AND ZH AT THE DIRECTOR

In the event of stable vertical failure, the main battery director takes over the job of measuring L' and Zh. The director pointer measures L'

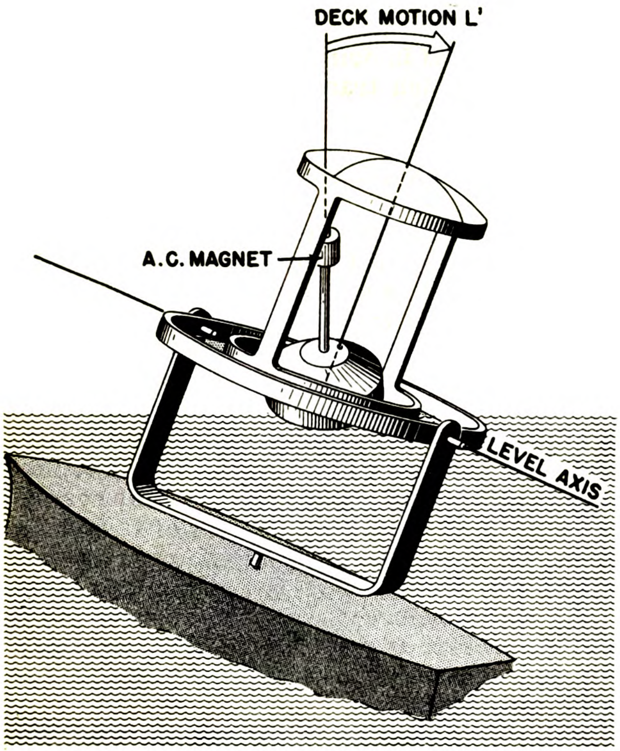


Figure 9-10.—Level error. 55.182

and another operator called the crosslevel operator measures Zh. These measurements are subject to human errors, but they are handy in an emergency.

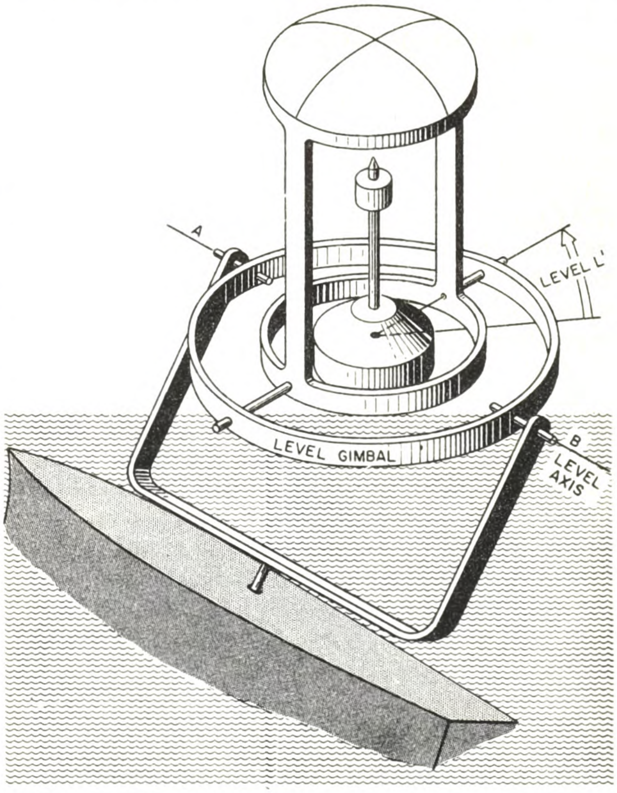
The pointer and crosslevel operator rotate their hand wheels to keep their crosswire on the horizon. The hand wheels, which are geared to synchro transmitters, transmit the measured quantities to the rangekeeper as shown in figure 9-14.

A study of figure 9-14 shows that the L' and Zh quantities measured by the director are received only by the trunnion tilt section at the rangekeeper as electrical inputs. This means that if deck tilt correction is to be used, L' and Zh must be cranked in manually at the stable vertical. This is accomplished by the stable vertical operators who observe the level and crosslevel dials on the face of the stable verticle. With everything in working order, it is possible for the deck tilt computer to receive L' and Zh automatically from the stable vertical, while the trunnion tilt computer gets its inputs from the director. This provides a split type of control. These different combinations of operation will be more apparent when you work with the gear.

Since you now know how L' and Zh are received at the rangekeeper, the next step is to see how the director does the measuring. Let's take the measurement of L' first.

Imagine that the director is trained out abeam, as shown in figure 9-15, and the pointer and trainer are sighting down the director LOS. The offset of the pointer's telescope from the reference plane (the reference plane is approximately parallel to the ship's deck) to the LOS is called DIRECTOR ELEVATION, E'b. When the deck is tilted as shown in figure 9-15, E'b contains L' (the angle between the reference plane and the horizontal at either the director or gun) and the director SIGHT DEPRESSION ANGLE.

Now, since E'd contains L', it should be apparent that all you have to do to get L' is subtract the depression angle from E'b. But it isn't that simple because the sight depression angle must first be computed. Look at figure 9-15 and try to visualize what would take place if the director and gun were located at the same level. Obviously, the director depression angle would then equal L'. Thus, the vertical distance of the



55.183
Figure 9-11.—Level angle after measurement.

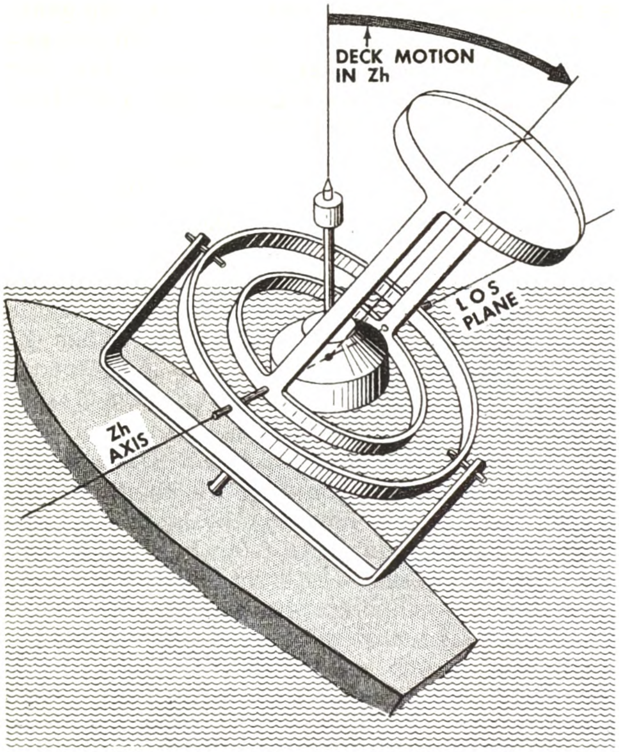


Figure 9-12.—Crosslevel error. 55.184

director above the gun is what causes the trouble. The difficulty is that the director and gun lines of sight are not parallel. Instead, they converge on the target at an angle known as VERTICAL PARALLAX, Pv. Vertical parallax is affected by the vertical distance between the gun and director, as well as by the range to the target. The computation of vertical parallax will be covered in a later chapter.

A further study of figure 9-15 will indicate that the director LOS can be thought of as a transversal cutting through two parallel lines (the horizontal lines at director and gun). Thus, the alternate-interior angles formed by the LOS and these horizontal lines are equal, i. e., the director sight depression angle is equal to Pv. Therefore, if Pv is manufactured in a mechanism at the director and subtracted from E'd, the director will transmit L' to the rangekeeper as desired.

Crosslevel, shown in figure 9-16, is measured by the crosslevel operator as he keeps his periscope horizontal crosswire on the horizon. Since Zh is measured as tilt across the LOS, the crosslevel sight is 90° away from the LOS as shown in figure 9-17.

The crosslevel operator cranks his hand wheels as he elevates or depresses his sight to the horizon, and in doing so, positions a synchro transmitter which transmits Zh to the rangekeeper.

DECK TILT CORRECTION

Thus far you have learned that the prediction problem is based on rates computed with the horizontal plane as a reference, and that the director measures target's present position with respect to the deck plane. We also know that the deck plane deviates from the horizontal plane and that therefore some method of stabilization is required to correct for deck tilt. We have seen that the amount the deck plane deviates from the horizontal plane, measured with respect to the LOS, is equal to the angles of L' and Zh. Hence, the quantities necessary to make the correction for deck tilt are known and available.

As stated before, the deck tilt correction is used to convert B'r' to Br. Let's investigate B'r' and see how it is converted to Br for use in the rangekeeper.

First consider the condition in which the deck plane of the ship coincides with the horizontal plane as shown in figure 9-18. You can see that B'r' is measured from the ship's centerline at plane E around to the line of sight at

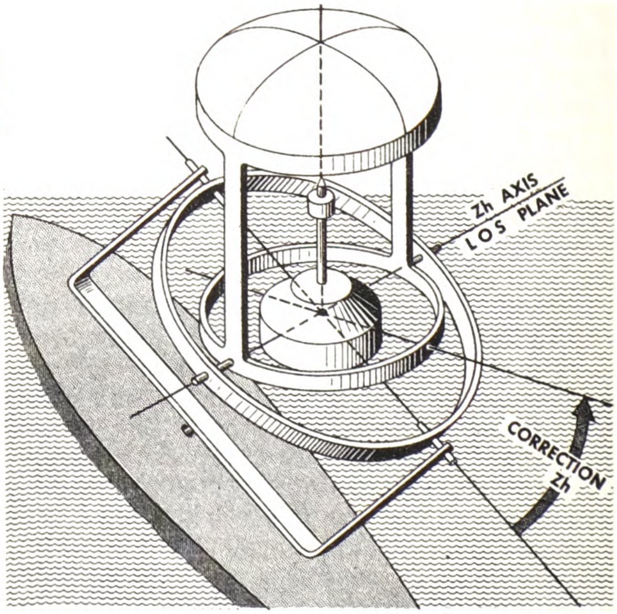


Figure 9-13.—Crosslevel angle after measurement. 55.185

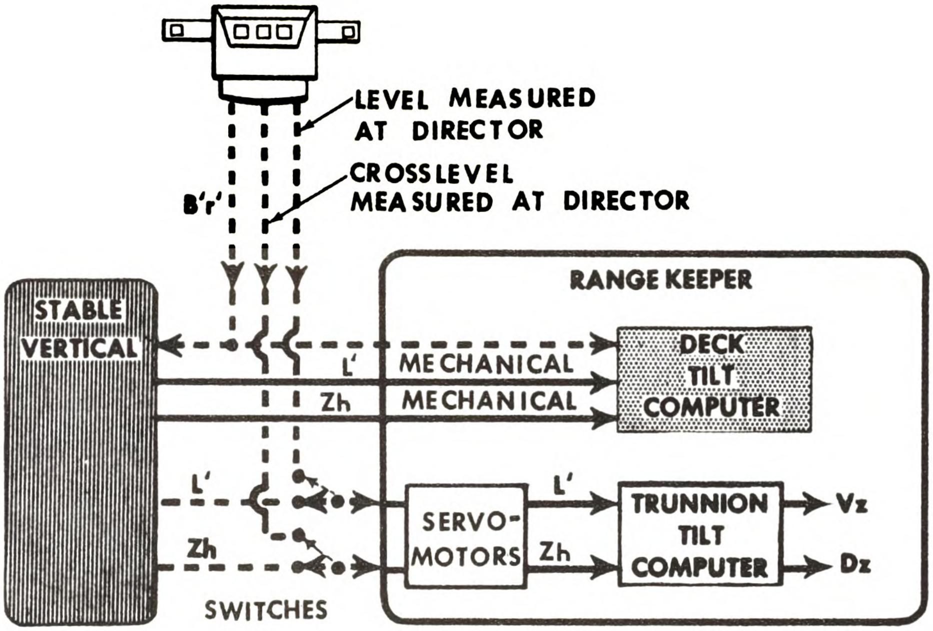


Figure 9-14.—Level and crosslevel measured by the director and transmitted to the rangekeeper by synchros. 55.186

plane A. And since the ship is horizontal, Br is equal to B'r'.

But the condition is different when the ship is tilted. When the deck is tilted through the L' and Zh angles as shown in figure 9-19, the director must be trained farther from the ship's centerline in order to indicate relative target bearing. Obviously, Br is no longer equal to B'r'. B'r' is now larger than Br. This points out why B'r' must be corrected when the deck is tilted, before it can be used by the rangekeeper to solve the prediction problem.

The job of converting B'r' to Br is performed by the deck tilt computer in the rangekeeper. Figure 9-20 shows that the deck tilt computer calculates a quantity called DECK TILT CORRECTION, jB'r', which is added to B'r' in a differential to give Br. As shown in figure 9-20, jB'r' is computed from B'r', L' and Zh.

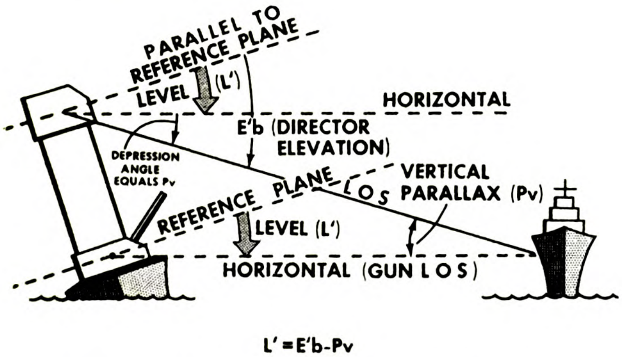


Figure 9-15.—How the director measures level. 55.187

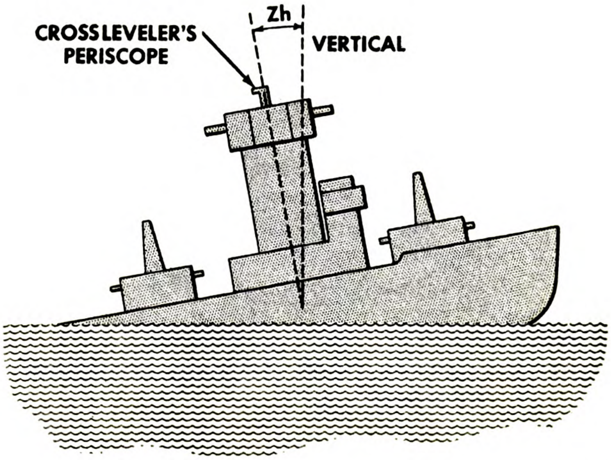
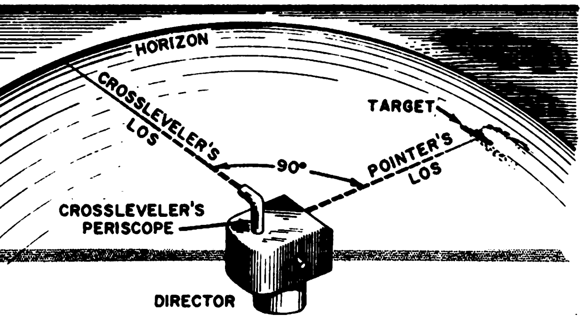


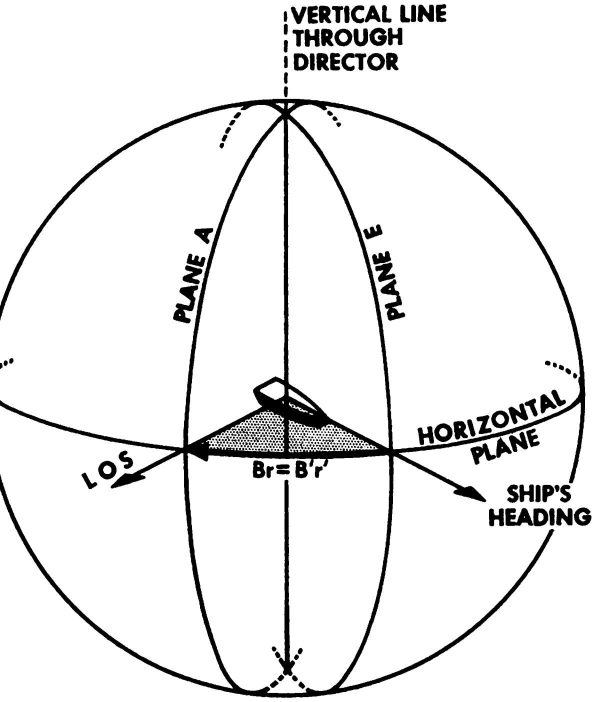
Figure 9-16.—Crosslevel as measured at the director. 55.188



55.189

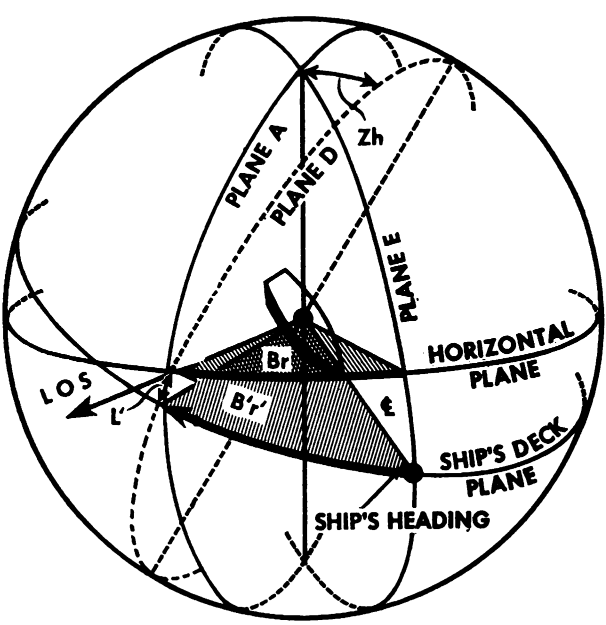
ure 9-17.—The crossleveler's periscope is ositioned 90° away from the LOS to the target.

Even though its mathematical solution is nplicated, you can see what part jB'r' plays studying figure 9-21. This is a magnified w of figure 9-19, with the jB'r' angle drawn



LANE A—VERTICAL PLANE CONTAINING LOS
LANE E—VERTICAL PLANE THROUGH CENTERLINE OF SHIP

ure 9-18.—Relative target bearing Br and director train B'r' are equal when deck is horiontal. 55.190



PLANE A	VERTICAL PLANE CONTAINING LOS
PLANE E	VERTICAL PLANE THROUGH CENTERLINE (℄) OF SHIP
PLANE D	PLANE PERPENDICULAR TO DECK PLANE CONTAINING LOS

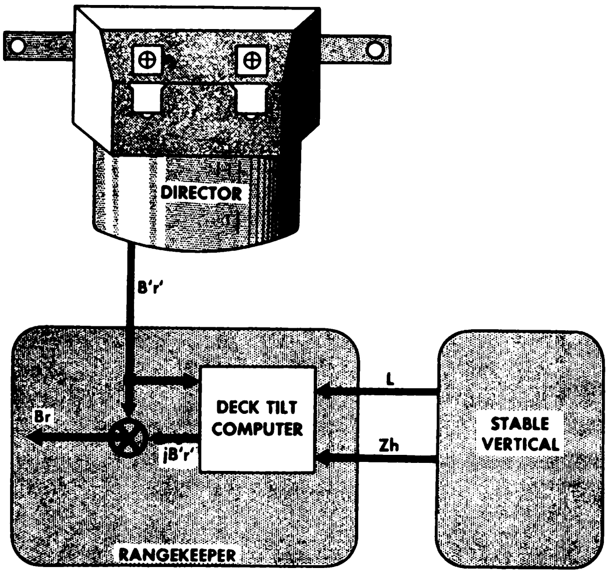
Figure 9-19.—When the deck is tilted, director train B'r' is no longer equal to relative target bearing Br. 55.191

A careful study of figure 9-21 will indicate that jB'r' is dependent upon both L' and Zh and the smaller these two angles are, the smaller jB'r' becomes. For the condition shown, B'r' is larger than Br so the deck tilt correction is subtracted from B'r' to give Br, or $Br = B'r' - jB'r'$. However, for certain other values of Zh and L', deck tilt correction is added to B'r' to give Br. Thus, in order to be correct at all times relative target bearing is given by:

$$Br = B'r' + jB'r'.$$

In this way jB'r' can change sign as L' and Zh change signs, and the problem will always work out right.

To get a better picture of how the deck tilt computer fits into the fire control system, refer to figure 9-22 and go through the diagram step by step starting at the director.



55.192

Figure 9-20.—Computing deck tilt correction.

When the director is sighted on a target, it measures B'r' which is transmitted to the stable vertical and deck tilt computer in the rangekeeper. Then the stable vertical measures L' and Zh with reference to the LOS and transmits them to the deck tilt computer.

The deck tilt computer then makes up jB'r' from the B'r', L', and Zh inputs and adds it to B'r' in a differential to give Br, which establishes a true horizontal plane for the calculation of range and deflection components in the linear rate section shown in figure 9-22.

The linear rates (dR and RdBs) are now calculated from the Br, R, and target inputs. These linear rates become the inputs to the prediction section where Vs and Ds are made up. As you already know, Vs and Ds contain all ballistic, wind, and relative motion corrections required to properly position the gun from the horizontal plane. For this reason, Vs and Ds also are accurate indications of the gun position only when the deck plane and horizontal plane coincide. This is one reason why the trunnion tilt computer is necessary. The trunnion tilt section of the rangekeeper manufactures the Dz and Vz corrections shown in figure 9-22. These corrections are added to Vs and Ds in the gun order section where the gun train and elevation orders are made up. You'll learn about trunnion tilt in the section immediately following.

HOW THE TILTED DECK AFFECTS THE GUN

The deck tilt of a ship can be considered as having two effects on the aim of a gun. One of these effects is to constantly elevate and depress the gun as a result of the level angle. This is shown in figure 9-23.

You can see from figure 9-23 that in order for the gun to remain in the LOF, L' (the correction) is added to Vs. When added, Vs and L' produce gun elevation order E'g. E'g is the elevation of the gun from the reference plane up to line of fire (LOF). The reference plane is approximately parallel to the deck plane. Of course, the LOF can be thought of as an extended line along which the gun must be fired to hit the target. Thus, in order to keep the gun positioned in the LOF, L' is continually added to Vs. It should be clear at this point that Vs is equal to E'g when the deck is level.

When the gun is trained abeam as shown in the upper drawing of figure 9-23, level is entirely dependent upon the roll of the ship and thus is very large. In this position it would be useless to try and fire without correcting gun elevation order by adding in L'. As the gun is trained ahead or astern, as shown in the lower drawing, the L' correction angle becomes less dependent upon roll and more dependent upon pitch.

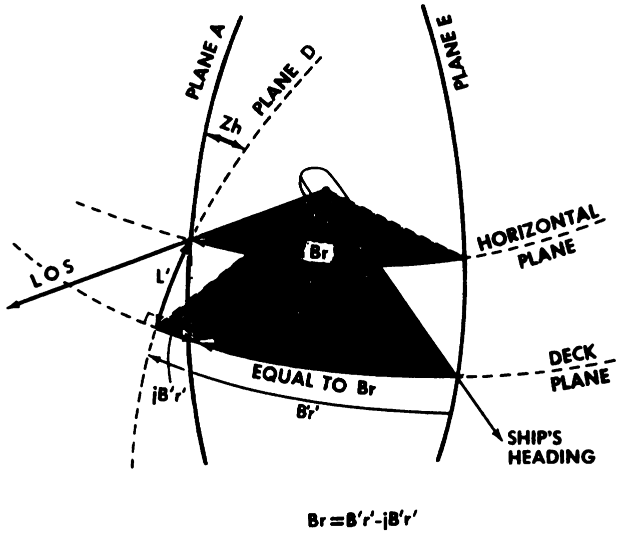


Figure 9-21.—When the deck is tilted about the LOS as shown, deck tilt correction jB'r' is subtracted from B'r' to give Br. 55.193

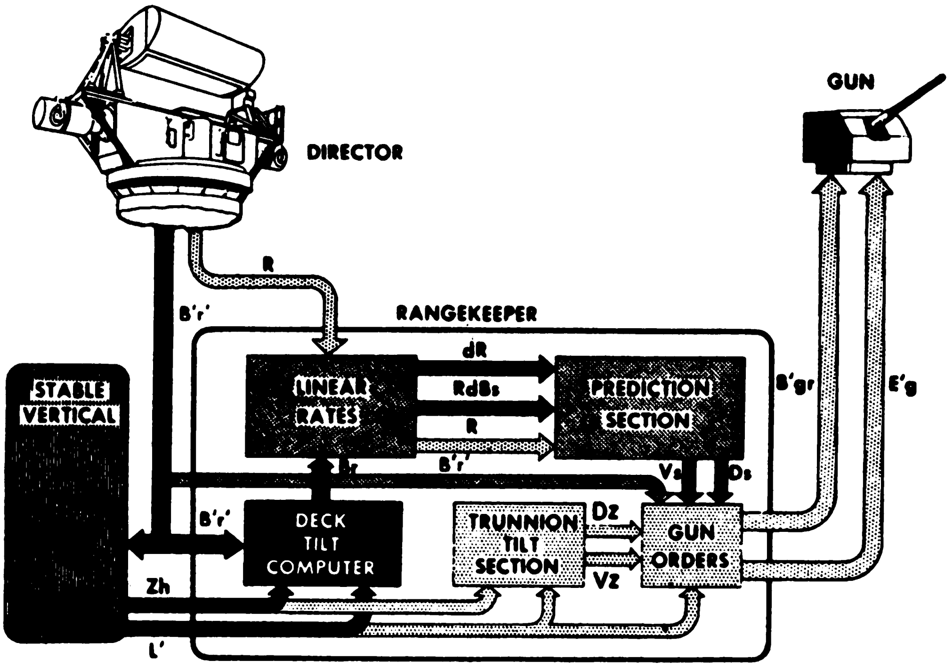


Figure 9-22.—Where the deck tilt computer fits in. 55.194

So much for level—the whole story is shown in figure 9-23. Level alone has no other influence on the gun than that shown. Gun elevation order is covered in the chapter on gun orders.

A second effect of the ship's movement is the tilt of the gun trunnions sideways. This effect is caused by cross level as shown in figure 9-24.

Even though our discussion has been confined to surface fire, gun elevation above the deck nevertheless presents a problem when Zh is present. Looking at figure 9-24 notice how the elevated gun barrel changes position when the gun trunnion axis is displaced from the horizontal by the angle Zh. Obviously, in order to hit the target, the gun must be trained and elevated back to its dotted-line position.

Figure 9-24 also shows the relationship between crosslevel and trunnion tilt. As can be seen from the diagrams, as crosslevel increases so does the trunnion tilt error.

The trunnion tilt errors must be corrected continuously and automatically in order to produce satisfactory results. This is accomplished by the stable vertical and trunnion tilt computer.

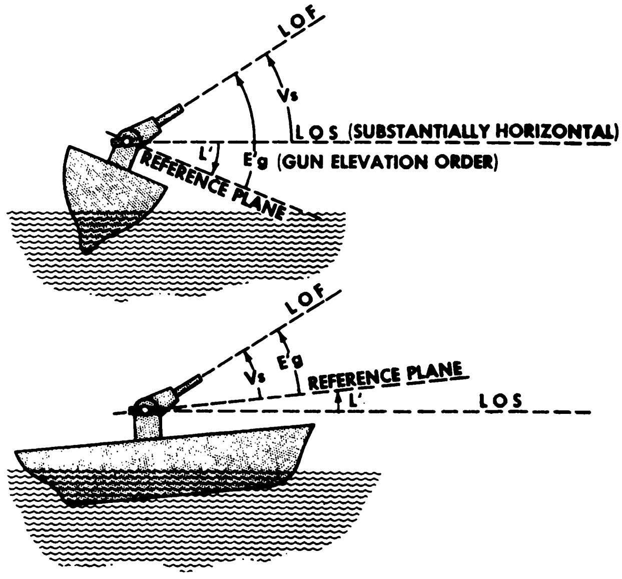


Figure 9-23.—How gun elevation is affected by the level angle. 55.195

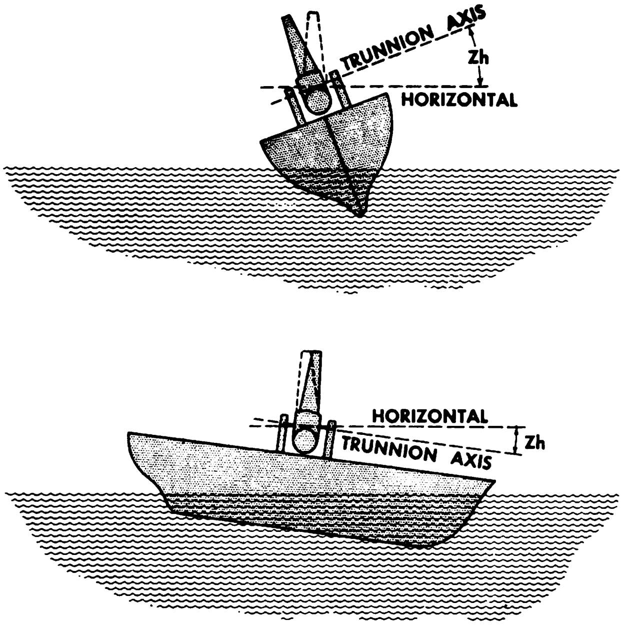


Figure 9-24.—How crosslevel affects the gun position. 55.196

TRUNNION TILT ERRORS

Firing without regard to trunnion tilt can result in large errors, especially in deflection. Roughly speaking, the deflection error in mils for surface fire is approximately one-third of the product of Vs and Zh. Thus, if the gun is fired at an elevation of 20° with the deck tilted so that Zh is 6°, the deflection error would be about 40 mils; that is

$$\frac{20 \times 6}{3} = 40 \text{ mils.}$$

At a firing range of 15,000 yards this is equivalent to a deflection error of 600 yards, or approximately one-third of a mile.

You can see the effect of trunnion tilt for surface fire in figure 9-25. GG' represents the axis of the bore of the gun when the trunnion axis AB is horizontal. In this case, if we assume that there is no deflection and no drift present, trajectory GT will lie in plane GG'T. The angle of elevation for the gun to hit the target will be TGG'.

Now if the axis of the trunnion is tilted through angle AGC, the axis of the bore of the gun will lie along line GG instead of GG', and angle G'TG'' will be equal to trunnion tilt AGC. The trajectory will now lie in vertical plane GG''P through the axis of the bore of the gun, GG''. Therefore, the projectile will land at the point T'.

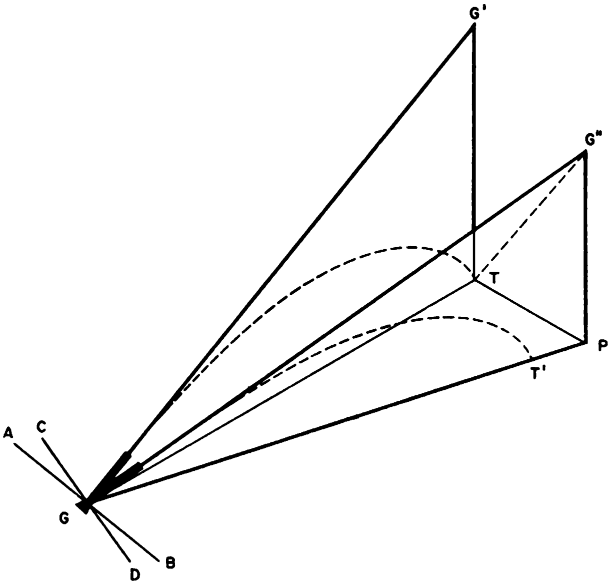


Figure 9-25.—Trunnion tilt errors. 55.197

This shows us that two errors result in figure 9-25. The first error is deflection error TP and the second error is range error PT', which is caused by the decreased gun elevation angle. Therefore the projectile will fall away from the target by amount TT'.

A study of figure 9-26 can tell you several things about trunnion tilt errors. First, that as Zh increases, the elevation of the gun decreases which increases the range error.

Figure 9-26 also shows that the deflection error will vary with the gun elevation and range. Deflection errors due to trunnion tilt will increase with range. At point blank range where the trajectory is flat, the deflection error will be zero regardless of how large trunnion tilt becomes for the bore axis will still point in the same direction no matter how far the gun trunnions are rotated.

In order to correct the errors shown in figure 9-26, the gun must be trained uphill to the left and depressed back on the target as indicated in figure 9-27. Although the error caused by trunnion tilt is largely a deflection error, its correction requires motion of the gun in both train and elevation.

These corrections are called train correction Dz in the slant plane and elevation correction

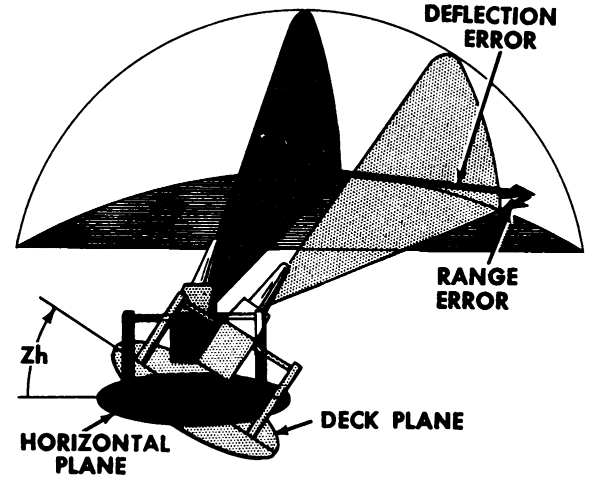


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Figure 9-26.—Effects of trunnion tilt.

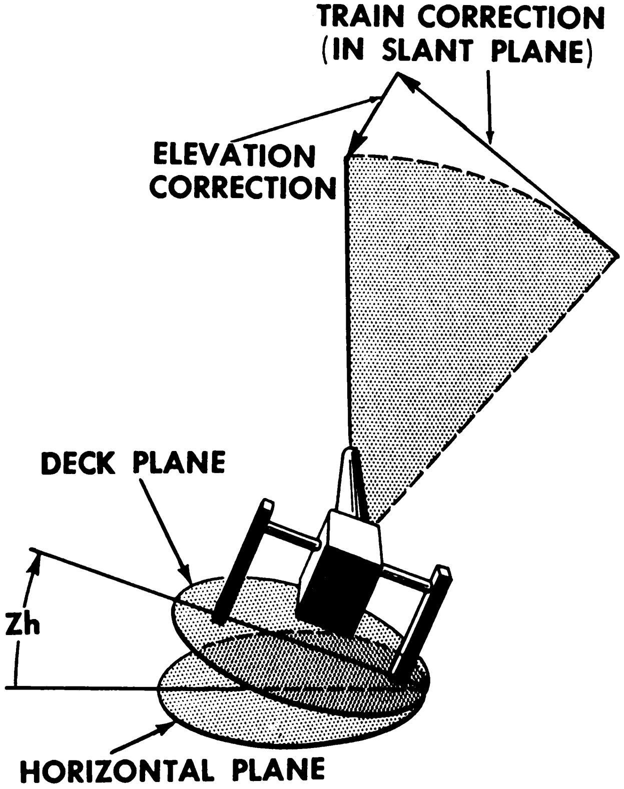

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Figure 9-27.—Correction for trunnion tilt.

Vz in a plane perpendicular to the deck through the bore axis.

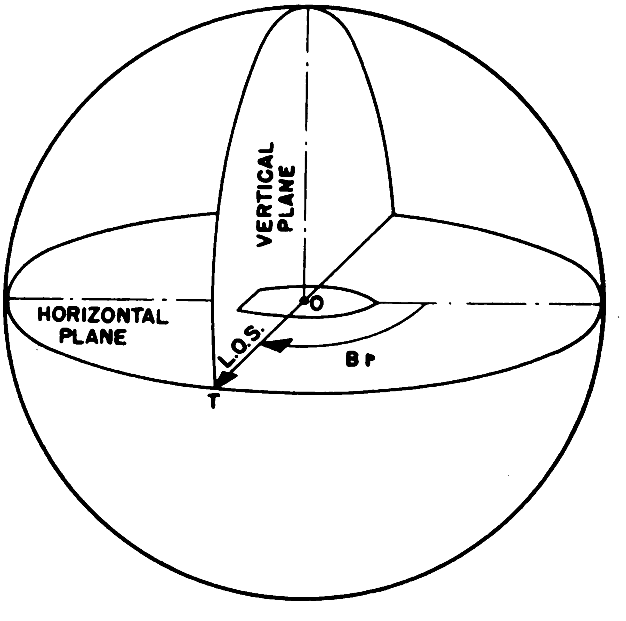
TRUNNION TILT ERRORS AND CORRECTIONS WITH NO DEFLECTION

The only way you can thoroughly understand trunnion tilt errors and their corrections is to study how they vary under different conditions.

Figure 9-28 shows the horizontal and vertical planes. The horizontal plane is always stationary and remains tangent to the earth's surface. The vertical plane is always perpendicular to the horizontal plane, and always contains the LOS; it shifts with the relative target bearing angle, Br. In the figure the gun is at O and the target at T, making LOS correspond to line OT. Since no deflection is present, the director and gun lines of sight coincide.

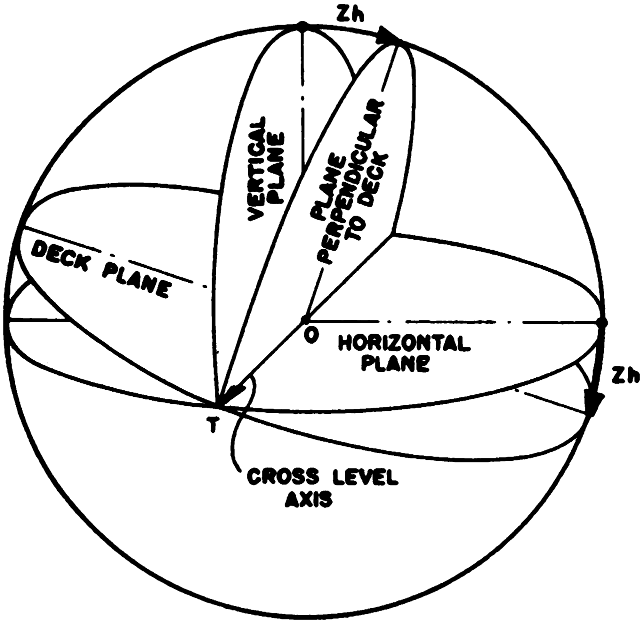
Although Br is used to determine the LOS relative to the ship's head, it is not shown in figure 9-29. It should be borne in mind, however, that the LOS is the reference for measuring L' and Zh.

In figure 9-28 the deck plane corresponds to the horizontal plane, but in figure 9-29 the deck plane is tilted by angle Zh about line OT, the crosslevel axis (LOS). Therefore, if the bore axis of the gun were elevated in the vertical plane with the deck horizontal, it would be carried



55.198

Figure 9-28.—Basic spherical diagram.



55.199

Figure 9-29.—Crosslevel (surface problem).

over to the vertical plane perpendicular to the deck, (called the normal plane) which is displaced from the true vertical plane by angle Zh. Thus, the LOF will be displaced from the vertical plane containing the LOS.

This displacement of the LOF can be clearly understood from figure 9-30. The line OE represents the initial or computed position of the LOF, with no deflection present. The gun initially lies in the vertical plane containing line of sight OT, and is elevated above the deck plane by angle E'g to position OE.

Now assume that the deck plane becomes inclined about axis OT by an amount equal to crosslevel as shown in figure 9-30. This will swing the LOF from OE to OE', lowering the gun aim and also creating a large angular error in deflection. The inclination of the deck will have no effect upon the angle the gun is elevated above the deck and the gun will be firing at a false point E' until the computed angle E'g is corrected.

The left diagram in figure 9-31 illustrates the corrections for the errors which were illustrated in figure 9-30. Let us correct the deflection error first. You know that the gun's roller path lies in the deck plane so that when it trains to get from its present position E' to the computed point of aim E, the projection of the LOF on the sphere will swing in an arc parallel to the deck plane. This motion is represented by the train correction a, which is an angular correction in the slant plane.

This train correction, a, is not enough to correct completely for Zh because it leaves the gun axis above the point E. The elevation correction Vz is required in solving the problem.

The right drawing of figure 9-31 illustrates the corrections for a Zh of the opposite or negative direction. When no sight deflection is present, the elevation correction Vz is always down.

Figure 9-32 repeats the situation shown in the right drawing of figure 9-31 with an additional angle shown. It shows how train correction a in the slant plane is converted to gun train correction Dz in the deck plane. In figure 9-32 Zh caused the gun bore to move to point E'. A study of the figure shows that train correction a and elevation correction Vz, both in the slant plane, have restored the gun to position E' in space.

The train correction a presents a problem because it is located in the slant plane containing the LOF as shown in figure 9-32. The gun must be trained through angle Dz in the deck plane of the ship to correct for train error a in the slant plane.

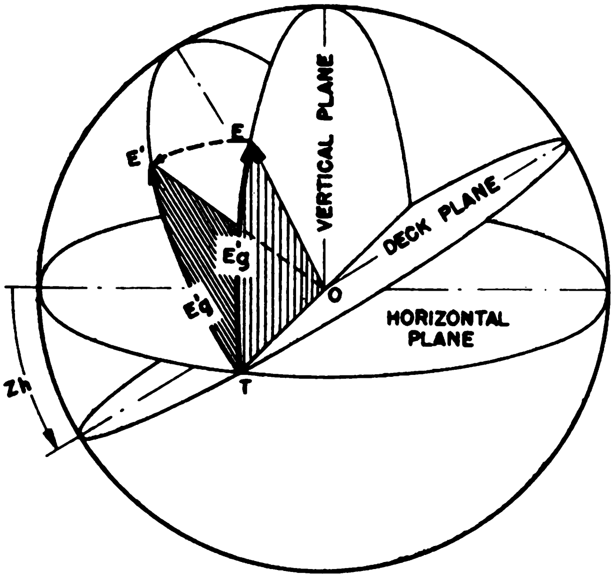


Figure 9-30.—Error due to trunnion tilt with no deflection.

55.200

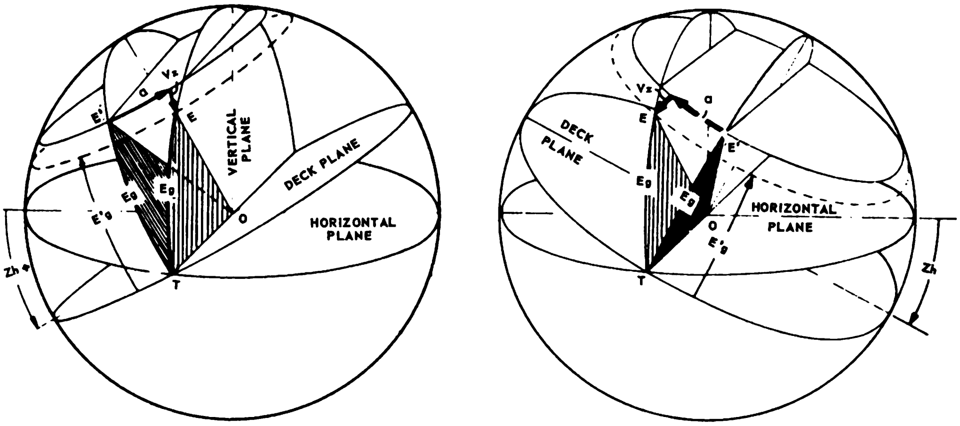


Figure 9-31.—Correction for trunnion tilt with no deflection. 55.201

Figure 9-33 shows how train correction a and elevation correction Vz vary with the gun elevation. If the gun axis is lying along OT, no correction is required; but as the gun elevates, both a and Vz grow larger. Since gun elevation depends on sight angle Vs, the trunnion tilt corrections increase as sight angle increases, and Dz will also increase.

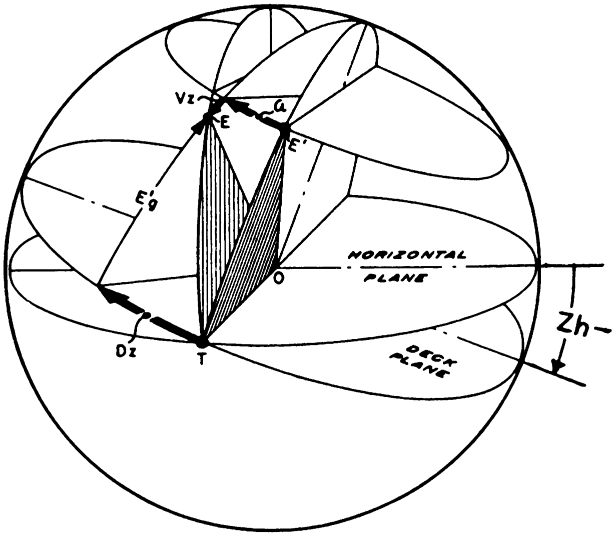


Figure 9-32.—Converting train correction a in the slant plane into train correction Dz in the deck plane. 55.202

TRUNNION TILT CORRECTION WITH SIGHT DEFLECTION PRESENT

The introduction of sight deflection Ds makes the problem more complicated in that Dz and Vz vary as Ds varies. Therefore, trunnion tilt corrections must take Vs and Ds into account.

Figure 9-34 shows the situation where the deck is horizontal. Sight deflection Ds in the horizontal plane, which now coincides with the deck plane is shown as well as the gun elevation above the deck plane, E'g. E'g equals the gun elevation above the horizontal, Eg, since the deck is horizontal.

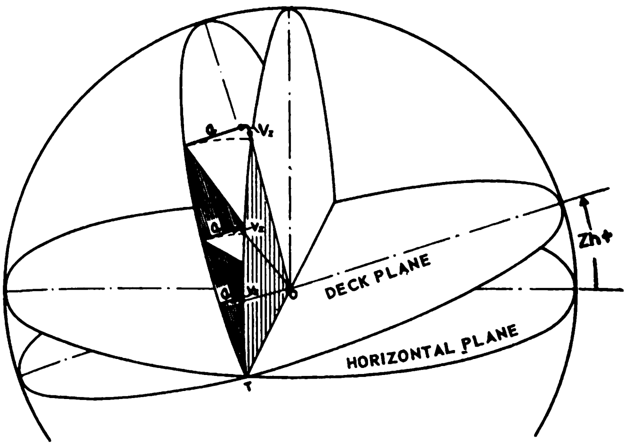


Figure 9-33.—The corrections, a and Vz, increase as sight angle increases. 55.203

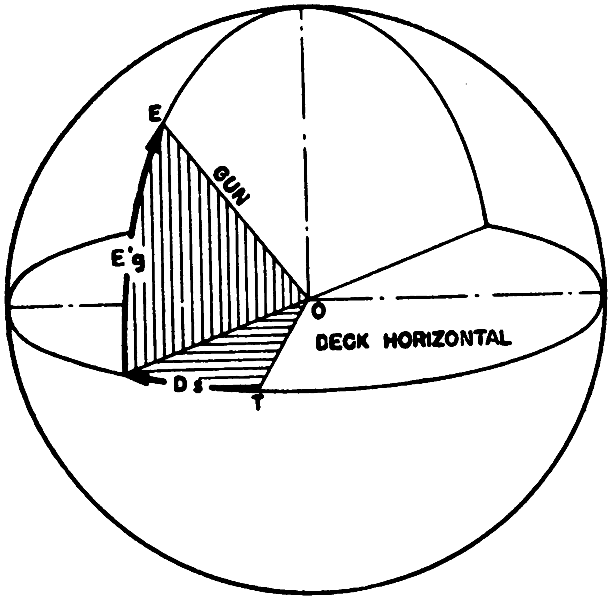


Figure 9-34.—Sight deflection causes no change in the position of the gun trunnions when the deck is horizontal. 55.204

Figure 9-35 shows the gun position when the deck is tilted by Zh, and Ds is present. A study of the diagram will tell you that two things happened to the gun position. First, the bore axis or the gun has been deflected to the left and elevated from point E to E', and second, the train of the gun in the deck plane remains essentially the same.

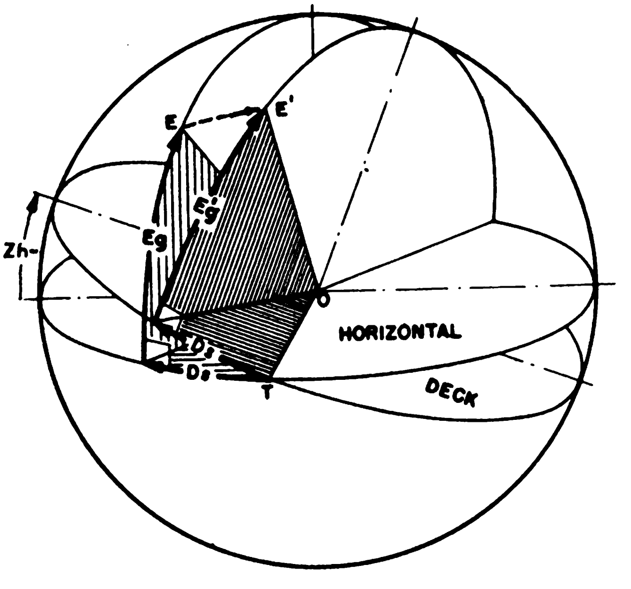


Figure 9-35.—Effect of crosslevel with sight deflection present. 55.205

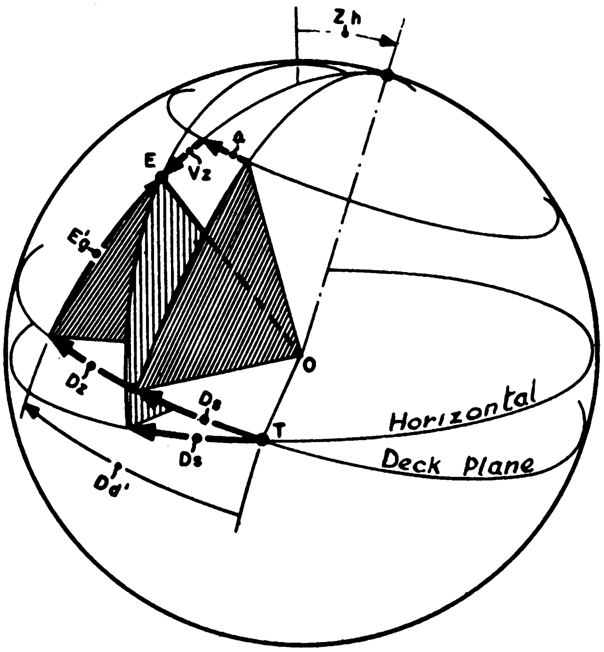


Figure 9-36.—Corrections for trunnion tilt with deflection present. 55.206

The corrections necessary to bring the gun back to the computed point E are shown in figure 9-36. Dz takes care of angular train correction a in the slant plane and Vz corrects the gun elevation. Notice that Dz correction is about the same size as when there was zero deflection, but Vz is much larger because the gun is positioned farther uphill as a result of Ds.

One new quantity is shown in figure 9-36. It is called DECK DEFLECTION Dd'. Deck deflection is the total amount the gun must be trained in the deck plane to correct for trunnion tilt plus all ballistics. And since Ds contains the corrections for all ballistics, and Dz is the train correction for trunnion tilt, then Dd' = Ds + Dz.

EFFECT OF LEVEL ON TRUNNION TILT

The effect of level on trunnion tilt is so slight that it is neglected altogether. However, it is very important to understand that level elevates and depresses the gun and must be allowed for. Therefore, level is added directly to Vz, in calculating E'g. L' hardly affects Dd' and is sometimes ignored. However, large values of L' will

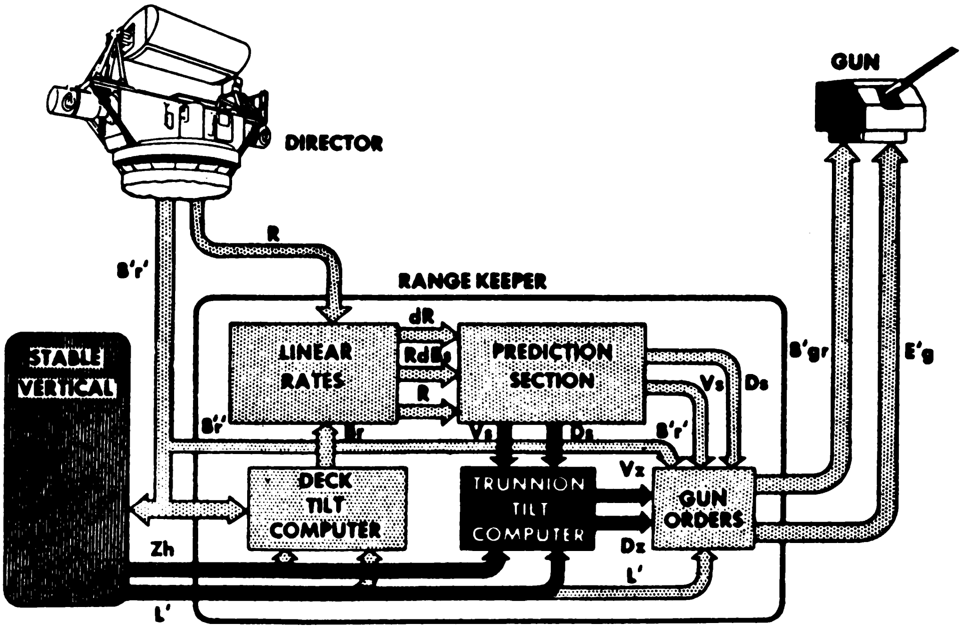


Figure 9-37.—Where the trunnion tilt computer fits in.

55.207

ve the effect of making Dz slightly over- rrected when Dz is large.

To sum it up, the trunnion tilt corrections ry with Vs, Ds, Zh, and to a small extent with vel, L'. The trunnion tilt computer shown in ure 9-37 takes Vs, Ds, Zh, and L' as inputs produce elevation correction Vz and train rrection Dz. The outputs of the trunnion tilt mputer are Vz and Dz and are combined with , Ds, and B'r' in the gun order section, which nsmits the proper E'g and B'gr to the gun.

The true equations for deck tilt correction d trunnion tilt contain terms which would re- ire a knowledge of spherical trigonometry to understand, and are therefore beyond the scope of this course.

If you are mathematically inclined, the true formulas can be found in Surface Fire Control, OP 1701 (First Revision).

Modified formulas for deck tilt and trunnion tilt are used in the rangekeeper. These formulas give a sufficiently correct value and do not require a long network of computing mechanisms. Due to the complexity of the true formulas and the fact that they are modified in the rangekeeper, the mathematical solution will not be covered here.

CHAPTER 10

GENERATED RATES

When we discussed the geometry of the problem in chapter 7, we considered it a static problem. The input quantities (R, Br, A, So and S), used to calculate the relative motion rates of range and bearing, were stationary or fixed values.

A little reasoning will tell you that even though own ship and target maintain their respective courses and speeds, the values of target bearing and target angle change continuously. And it follows that this will cause the relative motion rates to change continuously.

The changes in these values make this a dynamic problem. When tracking a target, we solve an infinite number of static problems, and in so doing generate a dynamic problem.

In figure 10-1, own ship is stationary while the target remains on a constant course and speed. We have selected an interval of time T. Note in the diagram that the target moves an equal distance along its track for each successive time interval. Also notice that target bearing, bearing rate, range, and range rate change in each successive time interval.

In the figure the changes are shown in steps or increments. This obviously is not satisfactory. The need for a continuous, smooth, and correct solution to the relative motion problem has been brought out previously. Let us now associate this need with the method used in the rangekeeper to establish the relative motion rates and the generation of range and bearing.

RANGEKEEPING

The rangekeeper is designed to keep range by generating a quantity know as GENERATED PRESENT RANGE cR (c is the symbol for generated). In all rangekeeper calculations cR takes the place of R. But first, before introducing the problem of generating cR, let's investigate what happens to range as the target moves.

In figure 10-1, as the target moves along its track, range initially decreases. This continues until relative target bearing is 90 degrees. At this point, range rate is zero. All target's motion is across the LOS. As the target moves past this point, range begins to increase. The speed with which range will change in the computer depends on the value of the range component of target movement.

The same reasoning applies to the movement of own ship. You can see in figure 10-2 that the rate at which range changes will depend on Yt and Yo. The sum of Yt and Yo is equal to range rate dR (where d is a sign meaning "rate of change of"), or dR = Yt + Yo.

Remember that dR is an instantaneous value and is true only for a given instant because dR changes as target angle and relative target bearing change.

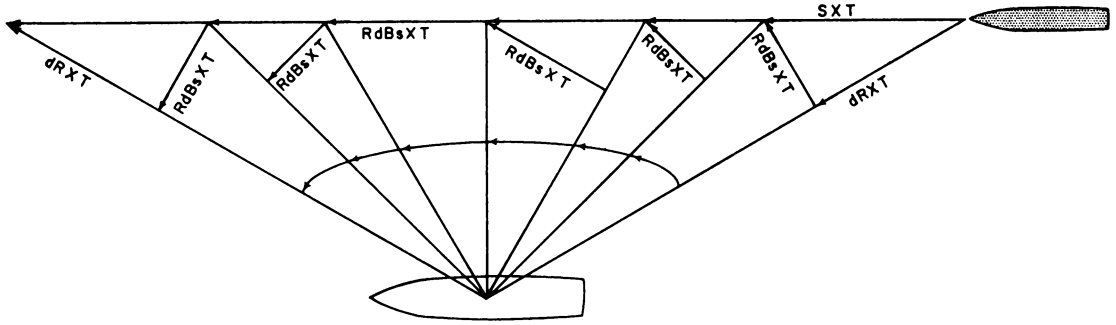
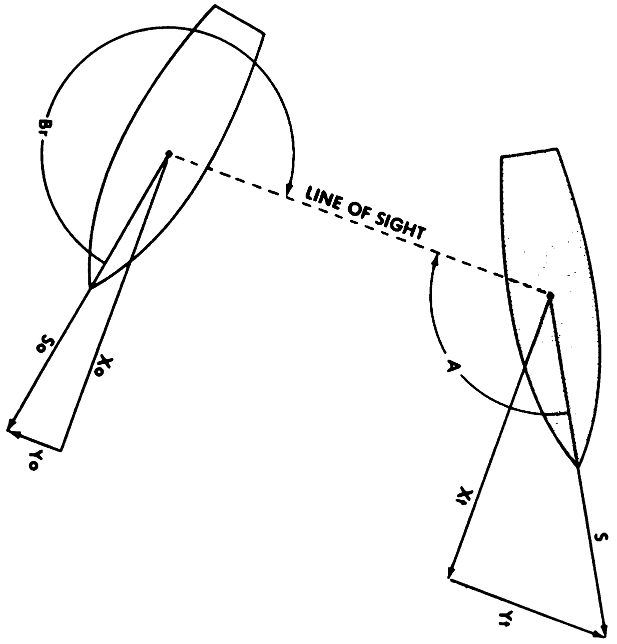


Figure 10-1.—Changes of bearings and range for successive time intervals. 55.208



55.209

Figure 10-2.—How range rate is obtained.

However, as long as Br and A are correct, even though they are always changing, the own ship and target component solvers will always furnish the correct value of dR, and dR will always indicate the speed with which range is changing at any instant. Therefore, in order to get the total change in range over a given period of time, all you have to do is INTEGRATE dR. That is, you multiply dR by time as time elapses and the result will be the total change in range in yards at the end of any given period of time. The integrator performs this function continuously.

RANGE INTEGRATOR

Let us examine the process of integration a little closer and assume that dR is equal to 20 yards/second. After 10 seconds the total change in range would be 200 yards, that is, change in range equals dR times time, or 20 x 10 = 200 yards. But this is not a typical case, as dR is always changing.

A better example would be to take several values of dR over a given period of time. Say that for the first 5 seconds dR is 20 yards/second, for the second 5 seconds dR is 25 yards/second, and for a third 5 seconds dR is 30 yards/second. Then at the end of 15 seconds the total change in range would be the sum of the products of each of the three dR's multiplied by the time over which each persists, or 375 yards:

dR1 x T1 = 20 x 5 = 100 yds.
dR2 x T2 = 25 x 5 = 125 yds.
dR3 x T3 = 30 x 5 = 150 yds.
Total change in range = 375 yds.

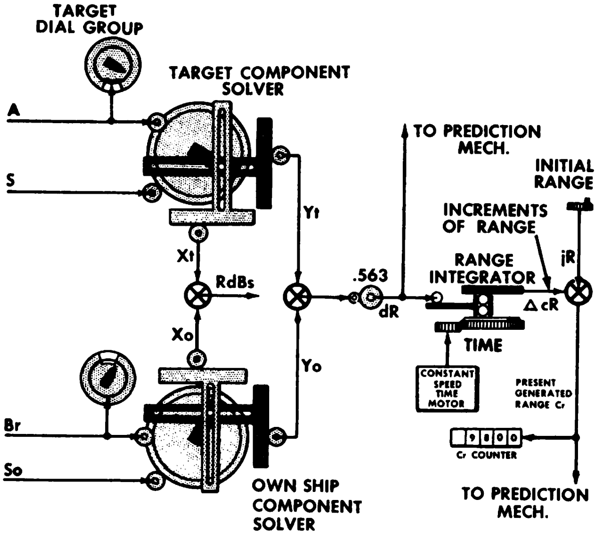
This is essentially the process of integration.

Now dR does not change in steps because neither target angle nor relative target bearing changes in steps; instead, dR changes smoothly. At one moment it may be gradually decreasing to zero and at another it may be increasing, but the change will always be like a smooth curve on a graph.

Given the changing values of dR, the range integrator is free to do its work. Using an infinite number of values of dR, the range integrator multiplies each value by the time over which it persists and continuously accumulates the products of these multiplications. The result is known as INCREMENTS OF RANGE, or ΔcR. The Greek letter delta, Δ, means either CHANGES IN OR INCREMENTS OF. Therefore, ΔcR will always give you the total change of range at the end of any given period of time.

The range integrator disk in figure 10-3 is driven at a constant speed by an electric motor known as the TIME MOTOR. The carriage is positioned by a rack and pinion, driven by the dR shaft. When the range rate is zero, the balls of the carriage are directly over the center of the disk and the disk rotation has no effect. However, if the range rate input has a definite value, the carriage and balls will be moved off toward one side of the rotating disk. When this occurs, the motion of the disk will be transferred by the balls to the roller. The roller will revolve at a speed which depends on the displacement of the carriage from zero. The amount of roller rotation represents increments of range ΔcR.

The accuracy of ΔcR depends upon the inputs of dR and time. The dR input is made up by the own ship and target component solvers (fig. 10-3). Therefore, the accuracy of dR depends on the accuracy of the component solver inputs. The inputs to own ship's component solver are measured quantities and therefore correct. The inputs to the target's component solver are estimated quantities. Therefore if an error exists in dR (computer functioning normally), it originates in the estimated inputs to the target component solver.



55.210

Figure 10-3.—Generated present range cR.

As you can see in figure 10-3, time is introduced into the rangekeeper by an electric motor. The output of the motor is maintained at a constant speed by a time motor regulator. This device is explained in Basic Fire Control Mechanisms, OP 1140. The passage of time is measured by shaft revolutions. This is not a new idea—a clock uses shaft rotation to measure time. The hands on the face of the clock are driven by shaft rotation, and indicate the passage of time. Here in the rangekeeper we have what amounts to an electric clock.

GENERATED PRESENT RANGE

With ΔcR being constantly generated, generated present range cR may be found by adding ΔcR to initial range jR. jR is measured by the rangefinder or radar, and the addition is made in a differential as shown in figure 10-3: $cR = jR - \Delta cR$.

With cR present in the rangekeeper, an accurate present range is available at all times for use by the computing mechanisms. This is so even when observed range is received from an intermittent source, such as an optical rangefinder or an indirect measurement made in CIC.

GENERATED BEARING

The rangekeeper is designed to generate true target bearing. If the target is momentarily obscured, the rangekeeper will maintain a correct target bearing in the absence of director train as long as the target maintains its same course and speed. Whenever the director trainer is on target, the rangekeeper operator compares the GENERATED and OBSERVED QUANTITIES and makes corrections when necessary.

Generated true target bearing cB is generated with the assistance of two integrators. cB is obtained by computing INCREMENTS OF BEARING, Δ cB, by integration and adding them to INITIAL BEARING jB. ΔcB indicates the TOTAL CHANGE in true bearing at the end of any period of time; at any instant ΔcB plus jB will give cB. Then if you subtract Co from cB, you will get GENERATED RELATIVE TARGET BEARING, cBr.

Linear deflection rate, RdBs, indicates how fast bearing is changing and is the key to solving for Δ cB. To arrive at the formula for ΔcB you must multiply RdBs by time. This gives the linear distance in yards tangent to the present range circle. But you want this change in bearing angle in minutes, so you divide by $\frac{cR}{1000}$, thus changing the linear distance to mils. Then to get minutes you multiply by 3.43. To state this mathematically, you have

$$\Delta cB = \frac{RdBs}{cR/1000} \times T \text{ mils} = 1{,}000 \times RdBs \times \frac{T}{cR} \text{ mils}$$

Or, by multiplying by 3.43 to convert mils to minutes, you have

$$\Delta cB = 3.43 \times 1000 \times RdBs \times \frac{T}{cR} \text{ minutes}$$

which is

$$\Delta cB = K \times RdBs \times \frac{T}{cR} \text{ minutes}$$

where K is equal to 3.43 times 1000, or 3430.

A sample problem will show you how the formula works. Suppose that RdBs is equal to 20 yards/second, the increment of time necessary to solve for range prediction is 10 seconds, and the generated present range is 10,000 yards. Solving for the bearing increments at the end of 10 seconds:

$$\Delta cB = 3430 \times 20 \times \frac{10}{10{,}000} = 69 \text{ minutes (approx.)}$$

The quantity RdBs, just as with dR, is constantly changing because the values of target angle and relative target bearing change. The integrator takes the changing values of RdBs and multiplies them by the time over which each persists and continuously adds the products. These products give ΔcB, which represent the total change in bearing at the end of any time interval.

The mechanical units which solve the formula for ΔcB are shown in figure 10-4. Present range cR, generated from the range-generation mechanism previously described, drives into a reciprocal cam to give $\frac{1}{cR}$. The same time motor that drives the range integrator also drives the inverse range integrator. The output of the inverse range integrator drives the disk of the bearing integrator and the carriage is positioned by RdBs. The roller of the bearing integrator will now turn at a rate proportional to the product of RdBs and $\frac{T}{cR}$. The output of the roller is ΔcB.

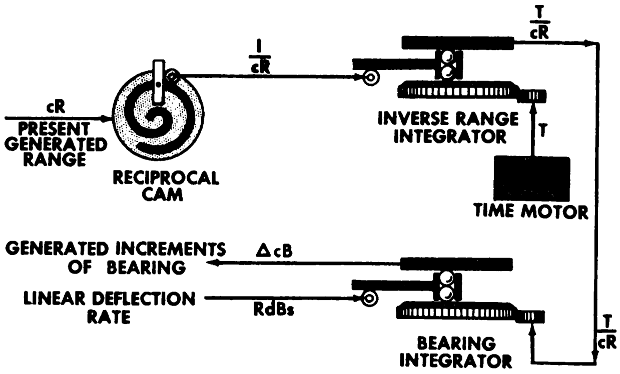


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Figure 10-4.—Generating increments of bearing.

Increments of Generated Director Train

When tracking a target in automatic control, the director and the rangekeeper are interconnected by synchros. The director automatically follows the changes in target position computed by the rangekeeper. Since the director is initially positioned on the target by the director trainer, only increments of director train are needed to keep it on the target automatically. For this purpose, the rangekeeper computes a quantity called "increments of generated director train ($\Delta cB'r'$)" from increments of generated true target bearing (ΔcB).

The quantity ΔcB is computed in the horizontal plane. To be used by the director, it must be referenced to the deck plane. The deck tilt correction, jB'r' (which was covered in the preceding chapter), is used to convert ΔcB to the deck plane.

Now we come to a tricky question about ΔcB. How can the rate, RdBs, which is made up by the relative angles of Br and A, when integrated with time produce increments of TRUE bearing? To answer this, we go back to see the relationship between true and relative bearing. This relationship is shown in figure 10-5 and in the formula

$$Br = B - Co$$

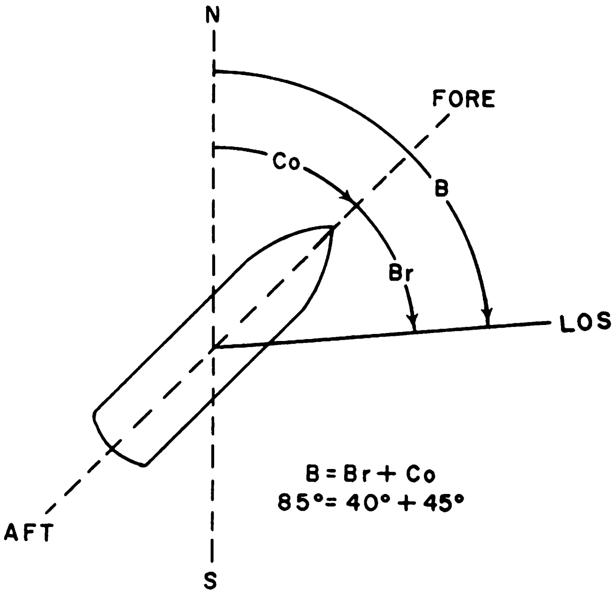

Figure 10-5.—Bearing angles. 55.212

The point to see is that any change in B will result in an equal change in Br. Therefore the increments of generated bearing can be added to true bearing and correctly called "increments of true bearing."

The reason the increments of generated bearing are added to true bearing can be seen if we give some thought to Co, the third quantity in the formula. The director measures bearing relative to own ship's bow. Therefore initially Co does not affect relative bearing; however any subsequent change in Co will affect relative bearing. Obviously the changes in relative bearing due to changes in Co must be compensated for. This is accomplished automatically by using true bearing and subtracting Co. In this way changes in Co are a part of $\Delta cB'r'$.

Figure 10-6 shows that $\Delta cB'r'$ is made up in the rangekeeper by adding ΔcB, Co, and jB'r'.

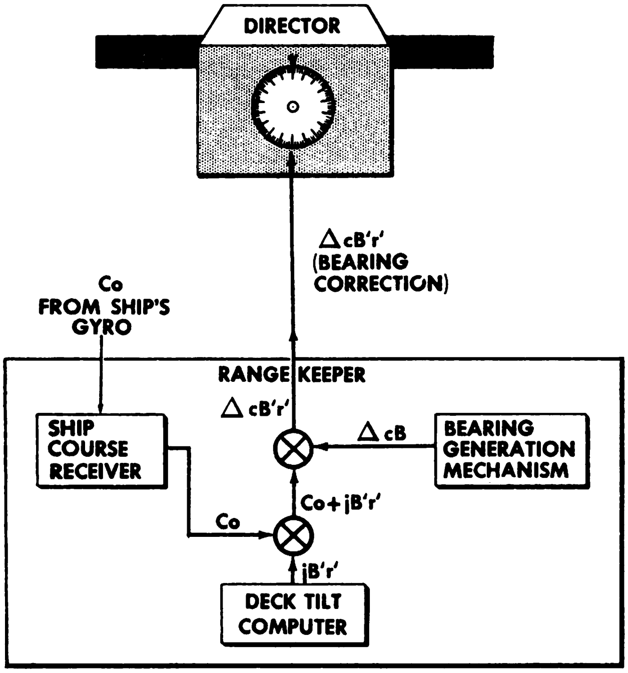

Figure 10-6.—Increments of director train are made up in the rangekeeper and transmitted to the director. 55.213

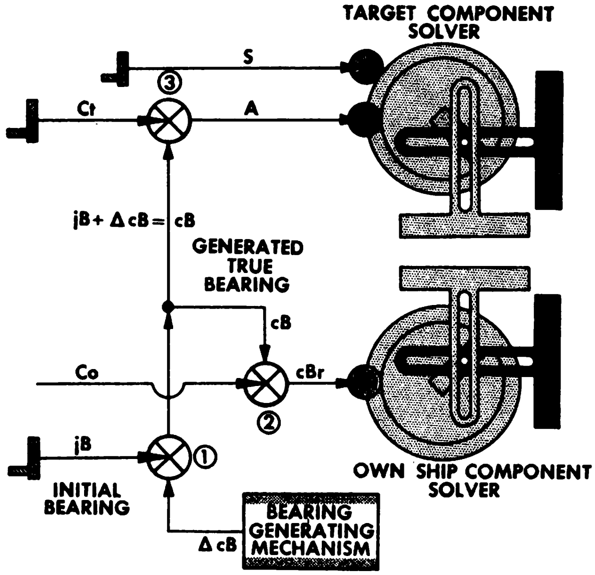

Figure 10-7.—How increments of bearing drive the own ship and target component solvers. 55.214

REGENERATION

Under normal tracking conditions, the target's range and bearing inputs to the rangekeeper are continuous. However, should the target become obscured, the rangekeeper must independently continue to compute the rates and generate target's position.

An arrangement which makes this possible is shown in figure 10-7. It can be seen that the quantity (cB) is used to make up cBr and A. These quantities are inputs to the component solvers which compute the rate (RdBs). The rate, when integrated with time, makes up cB. So, we have come around a complete cycle. cB makes up RdBs, and RdBs makes up cB. To put it another way, which will probably ring a bell, the input makes up the output and the output goes back to control the inputs. This is quite similar to the principle of feedback in servosystems.

A quantity in the rangekeeper is called a regenerative quantity when the output from its computing network is used as an input to the same network.

CORRECTING RELATIVE TARGET BEARING AND TARGET ANGLE

The regenerative arrangement of the bearing network provides a means of continuously correcting Br and A. The mechanisms which accomplish this are shown in figure 10-7.

Referring to the figure, the increments of true target bearing Δ cB are combined with initial bearing jB in the first differential. The input (jB) is the bearing of the target at the beginning of the problem. As the problem progresses, ΔcB either adds to or is subtracted from jB. The output of the differential is generated true bearing.

Co is subtracted from Δ cB in the second differential. The output of this differential is generated relative bearing (cBr). The reasoning behind using true bearing and subtracting Co is of course the same here as it was when we spoke of it when dealing with increments of generated director train. The input (cBr) to own ship's component solver is continuously corrected to the target's present position.

It remains to be seen how Δ cB can be used to correct A. Remember, we initially estimated A. Therefore, A has a definite value, although it is still an unproven value. Figure 10-8 shows

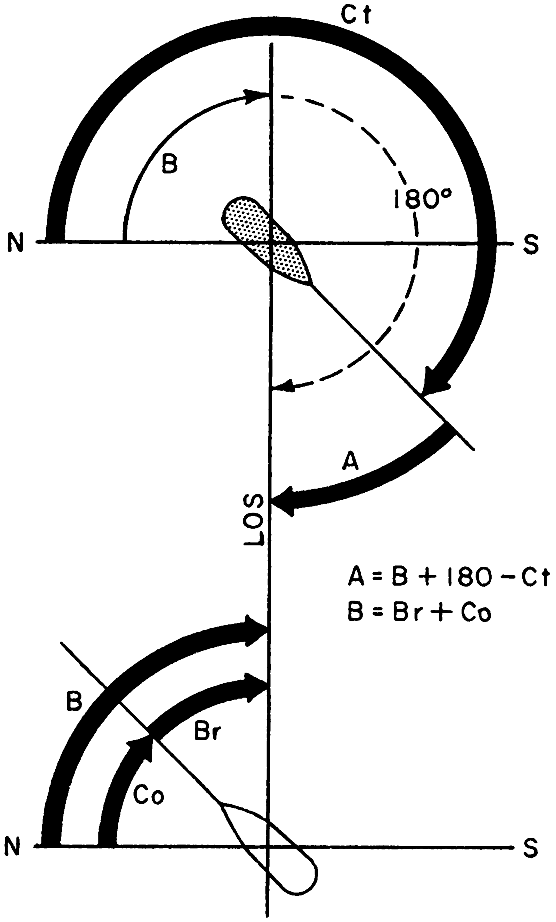

Figure 10-8.—The angles used to correct target angle. 55.215

the angles we will deal with in correcting A and the formula used to solve for A.

You will recall that A is a relative angle measured with respect to the LOS. It can be seen from the figure that if we add 180° to B, it will give us own ship's true bearing as measured FROM the target. Ct is subtracted to make the bearing of own ship FROM the target relative to the LOS. The last step is the same procedure we used to convert the target's true bearing to relative bearing by subtracting Co.

Figure 10-9 illustrates how ΔcB can correct target angle.

Refer to figure 10-9 and assume that own ship and target are at points 1-1 and are maintaining their courses. The initial true bearing (jB) is as shown. The angles Co, cBr, and A are also illustrated at point 1-1.

When both ship and target reach point 2-2, both cBr and A have changed to cBr1 and A1. At point 2-2 lines from both own ship and target have been drawn parallel to the original LOS between points 1-1. By referring to the line drawn from own ship parallel to the original LOS, it can be seen that angle ΔcB1 is the angle between the parallel line and the new LOS 2-2. Likewise, an increment of target angle, ΔA1, between the parallel line from the target and the new LOS 2-2, is drawn in.

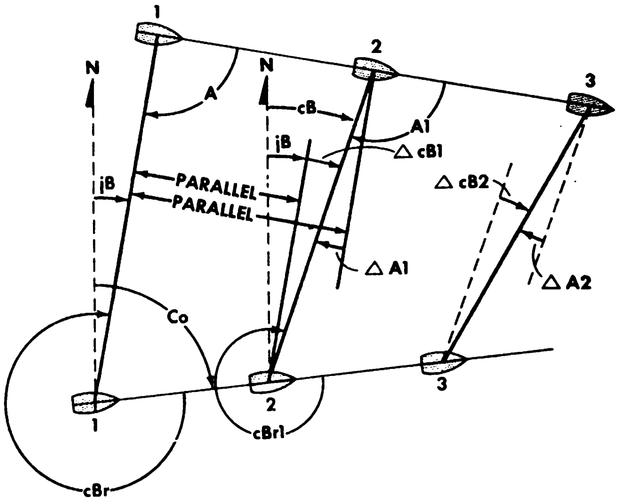

Figure 10-9.—How increments of bearing equal increments of target angle. 55.216

Since the lines from own ship and target are parallel to the original LOS, they are also parallel to one another. Therefore, the new line of sight between 2-2 is a line which intersects two parallel lines. Now, when two parallel lines are intersected by a straight line, the alternate interior angles are equal and so ΔcB1 is equal to ΔA1, that is, increments of target angle are equal to increments of bearing.

This explains why increments of bearing drive the angle gear of the target component solver in figure 10-7. Thus, once target angle is correct it will remain correct as long as the target holds the same course and speed.

Upon further inspection of the figure at point 2-2, it will be seen that cB equals jB plus cB1, the first total increment.

COMPARING THE GENERATED AND OBSERVED QUANTITIES

Another important feature of the generated quantities is that they provide a means of checking the relative motion solution of the rangekeeper. The accuracy of the solution is determined by comparing the target's generated present position with the target's observed present position.

The director tracks the target, measuring its position, and transmits to the rangekeeper the range and relative bearing (in the deckplane) of the target. After the initial setup, the rangekeeper tracks the target along with the director. Thus the rangekeeper computes (generates) the position of the target as it changes from instant to instant.

The dials on the rangekeeper are arranged to indicate the differences between the rate of change of the observed target position and the generated target position. By watching the dials we can compare the generated position with the corresponding observed position. The dials will indicate whether or not the generated and observed positions of the target are changing at the same rates.

If the values of dR and RdBs derived from the estimates of A and S were initially correct, the generated target position will agree at each instant with the observed position. If the initial values of dR and RdBs were incorrect, the generated and observed positions would not remain long in agreement.

When the latter condition is indicated by the comparison, the generated and observed values are rematched, and the process continued with new values of A and S. The process is repeated until a combination of A and S is found which causes the generated position to change at the same rate as the observed position. This procedure of comparing the generated with the observed quantities provides a continuous check on the relative motion rates, making it possible to quickly detect and correct errors in target angle and target speed as they develop.

RATE CONTROL

The relative motion rates, dR and RdBs, are established by a process of trial and error. But this process is not a haphazard one and does not take as long as you might think.

Remember, the relative motion rates are computed from known values of Own Ship Motion, known values of Target Position and ESTIMATES of Target Motion. When the target motion estimates are correct, the relative motion rates will also be correct. The process of correcting target speed and target angle is therefore called Rate Control.

The job of rate controlling is to analyze the differences between Observed Range and Generated Range, and between Observed Target Bearing and Generated Target Bearing. With this information, we determine what errors in Target Speed (S) and Target Angle (A) were responsible for the differences, and correct these errors.

It should be brought out here, at the beginning, that although own ship's motion is an integrated part of relative motion, it will not be considered as part of the rate control process. This is reasonable as it is a known factor. We should also realize that there is only one combination of A and S which will satisfy the conditions in the generation problem.

The process of rate control consists of using the differences between generated and observed target position to make corrections to A and S. The dials in the rangekeeper indicate the direction of the differences (errors) in terms of range changes and bearing changes. The direction of the differences tells you whether the generated changes of target position are too fast (leading the observed changes and creeping ahead of the observed values) or too slow (lagging the observed changes and falling behind the observed values). The speed of the creep will give you a good idea of the amount of correction necessary to A and S—the estimated quantities.

But there's more behind the story than that. How do you know whether to change the value of A or S, and how much should the erroneous quantity be changed?

You don't know exactly, but you can make a pretty good guess if you have taught yourself how to visualize the situation. Efficient rate control and the achievement of a quick solution demand a great deal of cooperation and practice. But the principles of rate control are quite simple if you know what to do about target angle.

Suppose the target is teaming on a course which is at right angles to the LOS, so that target angle is 90° or 270°. S has no range component at all, so range rate due to target movement is zero. The only effect of target movement is to change the bearing; that is, to cause a large bearing rate.

In this situation what would be the effect of doubling target speed? Obviously, it wouldn't change the range rate at all, but would double the bearing rate.

Similarly, at any target angle near 90° or 270° you will find that change in target speed causes only a small change in range rate, but a

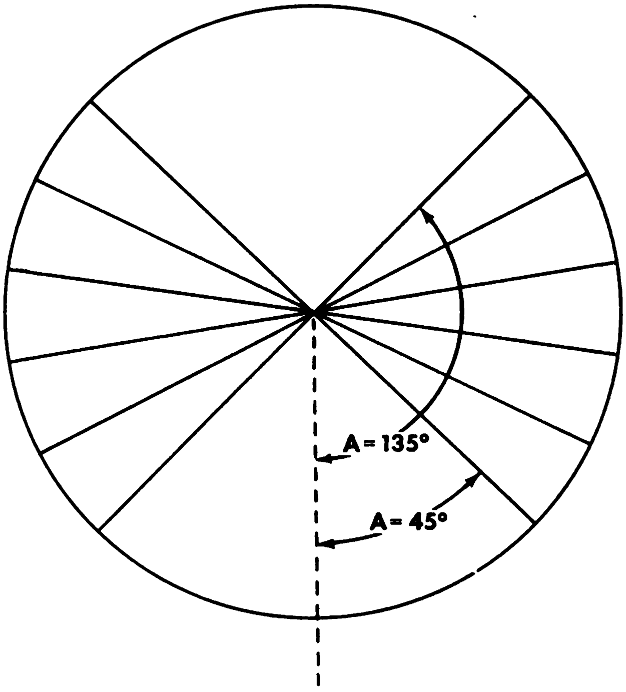

Figure 10-10.—If the target is headed along any of these lines, range rate is chiefly affected by target angle, bearing rate by target speed.

large change in bearing rate. You can see why in figure 10-10.

Under the same conditions, it is clear that a small change in target angle will have very little effect on bearing rate, but will change range rate substantially.

On the other hand, suppose the target ship is moving more or less along the LOS, so that target angle is in the neighborhood of 180°. In this case the speed of the ship is devoted almost entirely to opening and closing the range. Thus, any changes in speed will cause a large range rate change, but will change bearing rate hardly at all. And a change in target angle will change bearing rate without causing much change in range rate. This is shown in figure 10-11.

This is just the sort of information you need for rate control. Suppose the target angle is 80°; generated range is decreasing faster than observed range, and generated relative bearing is increasing faster than observed bearing. You can see at once that you must increase the target angle in order to decrease the range rate, and you must decrease the target speed in order to decrease the bearing rate.

Don't try to memorize rules about the changes to make at different target angles. Learn to visualize the situation and to figure out what needs to be done.

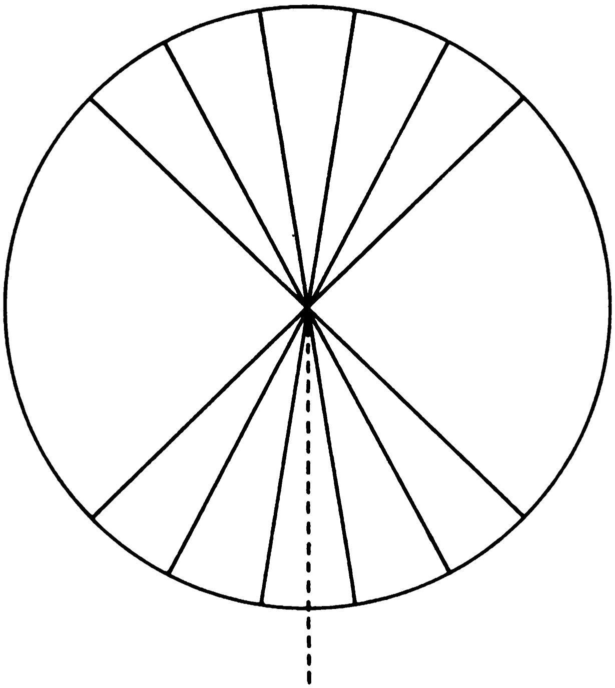

Figure 10-11.—If the target is headed along any of these lines, range rate is chiefly affected by target speed, bearing rate by target angle.

TRACKING SECTION

The function of the tracking section of a rangekeeper is to establish the relative motion rates, dR and RdBs, so that the change in target position during the time of flight of the projectile can be predicted.

The tracking section contains the mechanisms for setting up the problem, for computing the relative motion rates, and for comparing the observed and generated positions.

The tracking problem is solved by three groups of mechanisms: the deck tilt group, the relative motion group, and the integrator group.

The deck tilt group converts the relative target bearing from the deck plane (B'r') to the horizontal plane (Br). The relative motion group computes dR and RdBs, the relative motion rates. The rates are sent to the prediction section (where the future position of the target is computed) and to the integrator group. The integrator group generates changes in target present position by continuously generating Δ cR and ΔcB. The increments of generated range and bearing are used to correct R, Br, and A, which is correct, will keep the LOS on the target automatically.

The LOS is used as the reference to verify the rate of change of target position. The dials, which represent the LOS in the rangekeeper, are used to compare the observed values of range and bearing with the generated values. The tracking section allows us to measure target motion indirectly. Target motion is the only quantity in the fire control problem which we cannot control or measure directly.

The major advantage of this arrangement is that it establishes and CORRECTS the relative motion rates before we commence fire. Consequently, all the quantities upon which the predicted LOF is based are known factors.

THE AA FIRE CONTROL PROBLEM

The AA (air) problem, like the surface problem, consists of computing corrections so as to hit a target at a future time and at a predicted future target position. Obviously, there are differences due to the nature of the air target. Because the air target is above the surface of the earth, three coordinates are needed to determine its position. The air target is capable of movement about the three coordinates or axes at high speeds. Therefore predictions are computed in three dimensions, as shown in figure 10-12. The lead angles are normally large due to target speed; consequently, the ballistic correction must be computed about the LOF rather than the LOS.

The corrections necessary to establish an aiming point can be broken down into ballistic corrections and relative target motion corrections. The basic description of surface fire ballistics is also valid for AA fire; however, additional factors must be considered.

There are two methods widely used in the Navy to solve the AA relative motion problem. The first method, which we will take up in this chapter, is the linear rate solution. This is the method we used in the surface problem. The second method is the angular rate solution. This method is used in the GFCS Mk 63, and was described in the FT 3 training course.

BALLISTICS

The factors which influence the trajectory of a projectile can be considered first, thereby simplifying our later discussion of own ship and target motion, and predictions and corrections for the roll and pitch of the ship.

Gun Elevation

A projectile fired from a horizontal gun carries a relatively short distance. The distance, and consequently the time of flight, are increased when the gun is elevated. Other factors being constant, a given projectile will carry

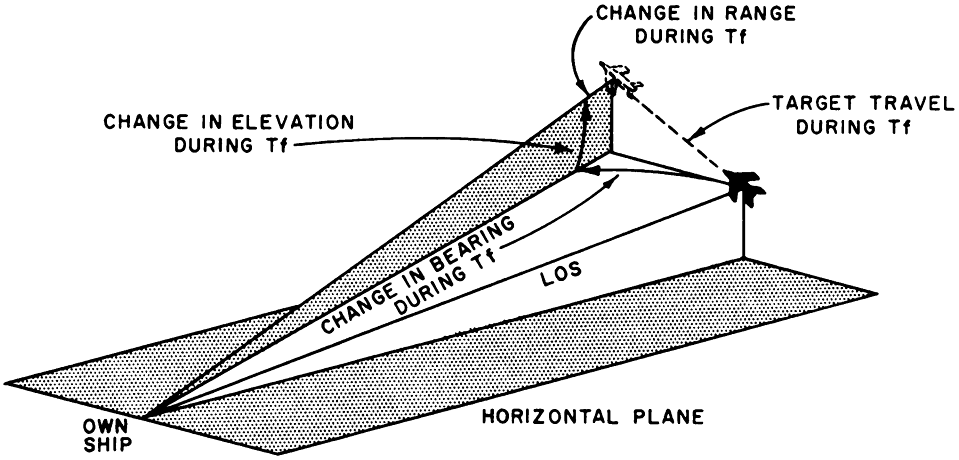
CHANGE IN RANGE DURING Tf
TARGET TRAVEL DURING Tf
CHANGE IN ELEVATION DURING Tf
CHANGE IN BEARING DURING Tf
LOS
OWN SHIP
HORIZONTAL PLANE

Figure 10-12.—Prediction for relative target motion, range, bearing, and elevation.

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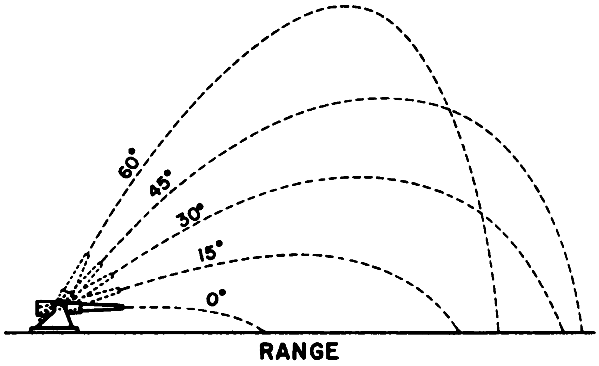


55.220
Figure 10-13.—Effect of gun elevation on the distance a projectile carries.

a definite distance and will have a definite time of flight for each elevation as shown in figure 10-13. Up to an angle of approximately 45°, the distance increases as the gun is elevated, but with further elevation the distance decreases and the maximum ordinate of the trajectory increases.

From figure 10-13 we can deduce that in the air problem, range and elevation are still related factors. However the height of the target above the surface of the earth must be considered. Target's height is measured by the elevation angle which establishes a slant plane containing the LOS. The LOF is contained in another slant plane called the prediction plane. The prediction plane is established with respect to the LOS by the corrections due to ballistics and relative motion. If you are not familiar with these planes, review chapter 2 of Fire Control Technician 3, NavPers 10173-A.

Superelevation

Superelevation is the component of gun elevation which compensates for the downward pull of gravity. The superelevation angles vary with future range R2 and future target elevation E2.

The force of gravity acts continuously on the projectile. Therefore, the longer the Tf, the greater will be the vertical deviation of the projectile from the LOF. Since Tf varies with R2, superelevation Vf also varies with R2.

In figure 10-14, three different projectile trajectories are shown for stationary surface targets at various ranges. It can be seen that as range increases, superelevation increases a proportional amount.

Now let's consider the elevated target. Elevation establishes a slant plane. The corrections to elevation must be made perpendicular to this slant plane. Gravity, however, acts perpendicular to the earth's surface in the vertical plane. Therefore the amount of deviation of the projectile from the LOF varies inversely with the elevation of the slant plane.

In figure 10-15, the Tf for the three stationary air targets is the same. The vertical force of gravity (G) is also the same. But the component of gravity perpendicular to the slant plane varies with the cosine function of the angle of elevation of the target's future position.

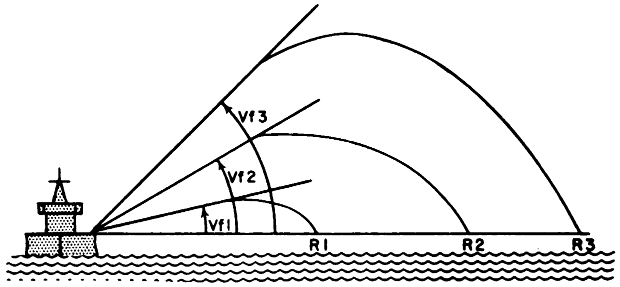


Figure 10-14.—Variation of superelevation with range. 55.221

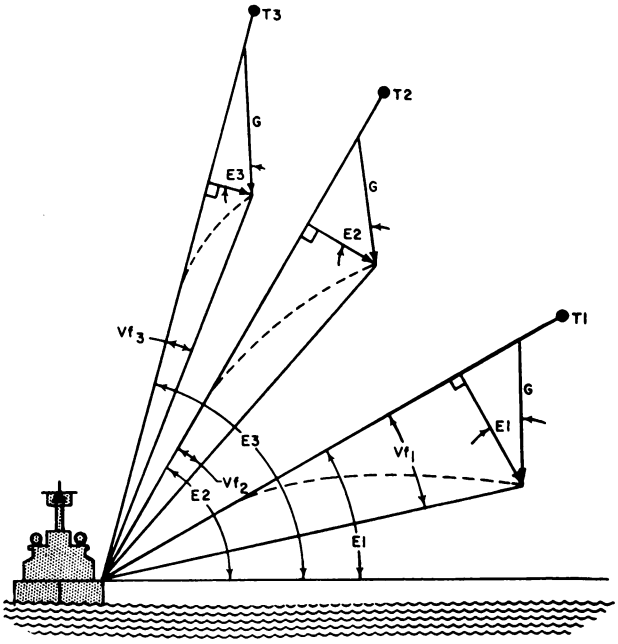


Figure 10-15.—Variation of superelevation with elevation. 12.20(55)

Drift

Drift is a projectile's tendency to move to the right of the trajectory it would follow in a vacuum.

Gun barrel rifling causes a projectile to rotate clockwise at high speed, thus imparting gyroscopic properties to it. These properties give the projectile a tendency to maintain its axis parallel to the line of fire throughout its flight. Since gravity pulls the projectile downward from the line of fire, its nose tends to remain elevated above a line tangent to its trajectory.

Drift of the projectile is caused by a combination of projectile inertia, reaction to air resistance, and gyroscopic precession caused by air resistance torques. Drift varies directly with the angle between the projectiles center line and the trajectory, and with the projectile's time of flight.

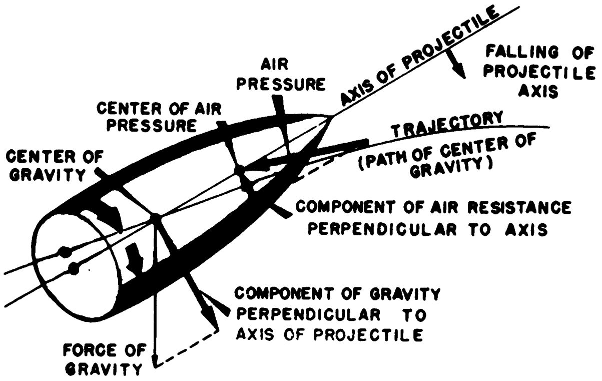

AXIS OF PROJECTILE
FALLING OF PROJECTILE AXIS
AIR PRESSURE
CENTER OF AIR PRESSURE
TRAJECTORY
(PATH OF CENTER OF GRAVITY)
CENTER OF GRAVITY
COMPONENT OF AIR RESISTANCE PERPENDICULAR TO AXIS
COMPONENT OF GRAVITY PERPENDICULAR TO AXIS OF PROJECTILE
FORCE OF GRAVITY

Figure 10-16.—The effect of gyroscopic stability. 55.222

Let us see why drift is related to superelevation. When the projectile leaves the gun, its trajectory is constantly curving downward, away from the line of departure. The projectile is spinning rapidly so that its gyro stability tends to keep it pointing in one direction. But it is following a curved path. The nose of the projectile, therefore, tends to rise above the line of the trajectory as shown in figure 10-16. As soon as its nose rises, air pressure on the underside tries to push its nose farther upward. Because it is a gyroscope, the projectile resists this force and precesses to the right. Soon the projectile's nose is to the right of the trajectory, and air pressure tries to push it farther right (fig. 10-17). This causes downward precession, which continues until the nose is below the trajectory line. Thereafter, precession is to the left and downward, until the nose is left of the line of fire; then upward and to the left until the nose is above the line of fire; then to the right and upward until the projectile nose is right of the line of fire. Thus, whenever the nose is above the trajectory, the projectile precesses to the right, and when it is below the trajectory, it precesses to the left. This causes the average position of the shell to be along the trajectory, i.e., it tends to remain tangent to the trajectory path.

Remember, though, that when the shell moves along the trajectory it is constantly falling downward. This causes the nose of the projectile to remain above the line longer than below. The net result is that the air pressure acting on the underside of the projectile nose causes a rightward drift. The correction is, of course, always to the left, and is considered negative.

You can see that the amount of drift will depend upon the curvature of the trajectory. And

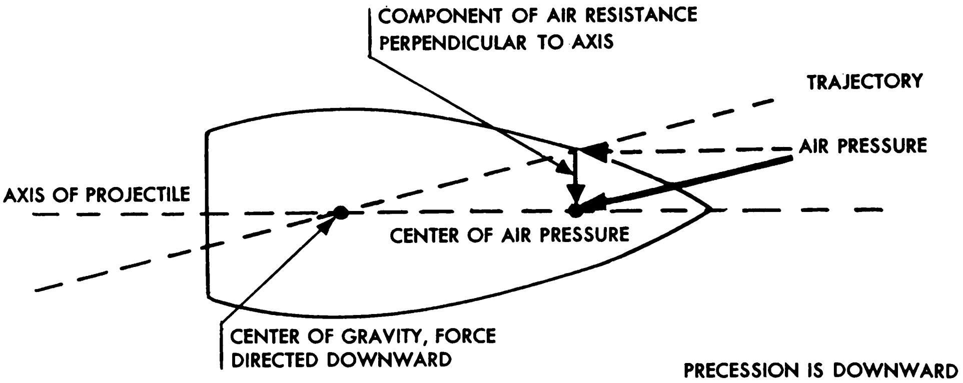

COMPONENT OF AIR RESISTANCE PERPENDICULAR TO AXIS
TRAJECTORY
AIR PRESSURE
AXIS OF PROJECTILE
CENTER OF AIR PRESSURE
CENTER OF GRAVITY, FORCE DIRECTED DOWNWARD
PRECESSION IS DOWNWARD

Figure 10-17.—Effect of precession, looking down on the projectile. 55.223

the curvature of the trajectory depends upon superelevation. The amount of drift is therefore proportional to and varies directly with superelevation.

Total linear deflection due to drift is approximately equal to the rate of drift times the Tf. And the deflection angle in mils due to drift Df will be the linear drift divided by future range in thousands of yards.

Changes in Initial Velocity

The values of superelevation, Vf, and drift Df give you the complete picture of the AA trajectory under theoretical range-table conditions with a motionless target, standard initial velocity, and still air of standard density. However, the laboratory conditions under which these quantities are calculated never exist in practical gunnery. So, just as in surface fire, it is necessary to correct for variations from the standard.

If the projectile travels slower due to the loss of I. V., it will take longer to cover any 100-foot length of the trajectory. Gravity will have longer to act, and the projectile will fall farther. Thus the actual trajectory will be more curved and shorter than the standard trajectory, as is shown in figure 10-18. As a result, the projectile will fall short; it will cross the LOS at less than the proper slant range. The error shown in figure 10-18 is the distance AT.

This error is allowed for in AA gunnery in about the same way that it is in surface fire. The slant range is increased by an amount equal to the error. A moment's thought will show that distance AT is roughly equal to (I.V. loss) x Tf. Therefore, this quantity is added to slant range, and a superelevation corresponding to the revised range is used.

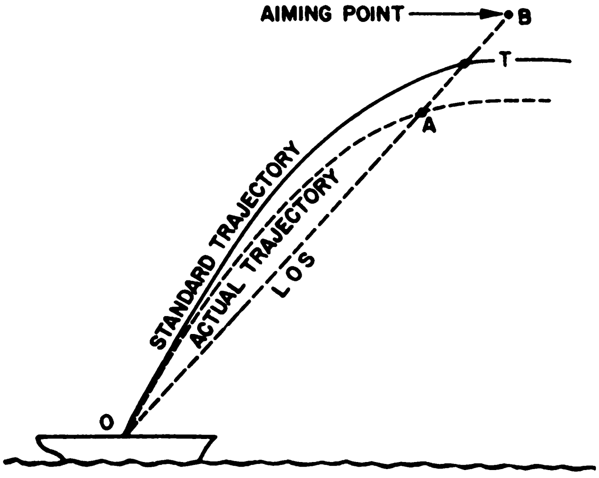


Figure 10-18.—The error due to changes in initial velocity.

55.224

How Wind Affects AA Fire

As with surface fire, corrections for wind in AA fire are only approximate. The correction due to wind is based on the assumption that wind is always horizontal and its force and direction are the same throughout the trajectory of the projectile. Sometimes a ballistic wind is used. More often, however, time doesn't permit a calculation of a ballistic wind, so the observed wind is used.

The first step in computing a wind correction is to separate the wind into range and deflection components. The method of resolving wind into its component vector here is a little more exact than the method used in surface fire. In the surface problem you obtained components along and across the LOS. The angle Ds between the line of sight and the line of fire was so small that it could be disregarded in wind computations. But in AA fire you have to lead a fast target, which makes a large angle between the line of fire and the line of sight. Components of wind are therefore taken along and across the LOF in computing the AA problem.

In order to obtain the wind components relative to the LOF, you figure out the angle between the wind and the LOF. This angle is called Bwg. Figure 10-19 shows you how the various angles involved are measured. Bw is the direction from which the wind is blowing, a known quantity. B is true target bearing, which can be obtained by adding measured relative target bearing to own ship's course, and Ds is the deflection angle. Therefore

$$Bwg = B + Ds - Bw$$

There is an approximation in this use of Ds which will be explained later, but it is accurate enough for the purpose. The components of wind speed Sw can be computed by taking Bwg as one input to a component solver and Sw as the other input. The outputs would then be range component of wind Ywg, and crosswind component Xwg.

The wind acting on the projectile is apparent wind. To obtain the range and crosswind components of the horizontal apparent wind, we add

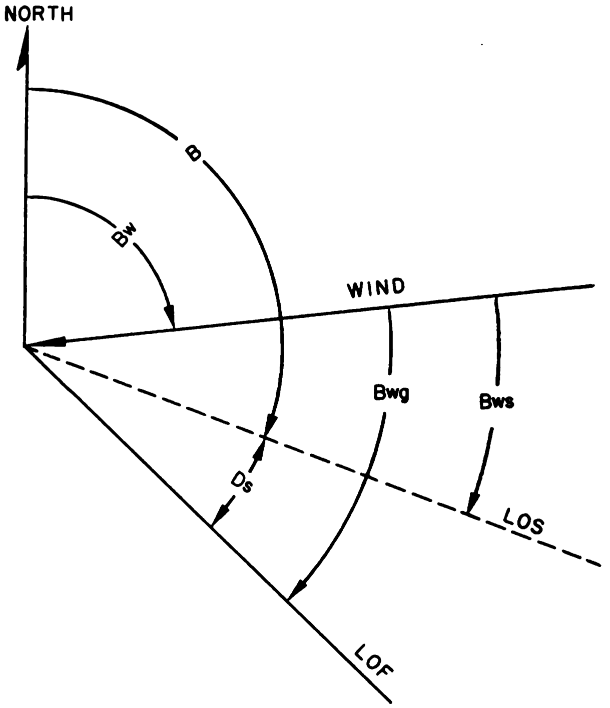


Figure 10-19.—Wind angles about the line of sight. 55.225

the components of own ship's motion to the corresponding components of true wind.

$$Ywgr = Ywg + Yo$$
$$WrD = Xwg + Xo$$

This is the same procedure we used in the surface wind problem. WrD is the apparent wind velocity affecting the deflection prediction. The solution for the deflection wind rate is completed.

Actually, Yo and Xo are computed relative to the LOS rather then the LOF. But since Yo and Xo are already available in the computer, they are generally used.

WIND IN DEFLECTION.—The effect of crosswind is the same in AA fire as in the surface problem. The projectile is pushed sideways. The distance of displacement depends upon the force of the crosswind and the time of flight. You'll remember from your study of the surface problem that linear deflection due to wind is equal to the deflection wind rate (WrD) multiplied by time of flight. However WrD is initially measured in knots. Therefore we must convert to yd/sec and then to angular mil measure. The formula for Dw is:

$$Dw = \frac{WrD \times Tf \times 563}{R2}$$

RANGE COMPONENT OF WIND.—We now must consider the effects of the range component, Ywgr, on the projectile's trajectory. Although this is referred to as a range component, you must realize that it is not directed along the LOF. It is a horizontal component which lies in the vertical plane containing the LOF. In figure 10-20, Ywgr is drawn in a horizontal plane parallel to the ship's horizontal plane. In this particular example, Ywgr is a negative quantity (decreases range). If Ywgr were a positive quantity it would be drawn in the same plane but on the opposite side of the LOF and all the arrowheads would be reversed.

In the figure it is obvious that Ywgr has two effects on the trajectory. The component of Ywgr acting ALONG the slanting line of fire is working to slow down the projectile, hence is a range factor.

This slant range component of wind is called WrR. From figure 10-20 we see that

$$WrR = Ywgr \cos E2$$

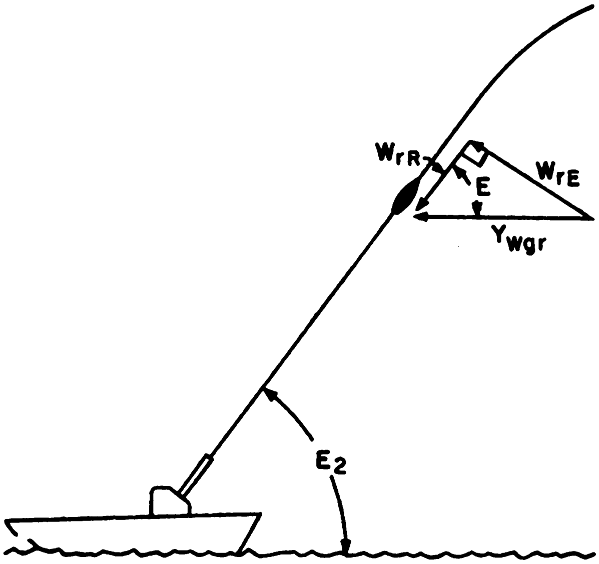


Figure 10-20.—The horizontal range component of wind.

55.226

The approximate formula to compute the range correction for wind (Rw) is

$$Rw = WrR \times Tf \times 0.563$$

This leaves one other component of wind to derive. It acts on the projectile perpendicular to the LOF, as shown in figure 10-20. A study of the figure indicates that this component of wind necessitates a correction to elevation. The elevation wind component, WrE, is computed from the formula

$$WrE = Ywgr \sin E2$$

The elevation wind correction, Vw, is added to sight angle which is measured in minutes of arc. Therefore, Vw must be converted from knots to yd/sec, then to angular mil measure, and finally to minutes of arc. This can all be accomplished by combining the steps, and by the use of the constant 1936 divided by future range.

The approximate formula for Vw is

$$Vw = \frac{WrE \times Tf \times 1936}{R2}$$

When Vw tends to carry the projectile toward the horizontal plane, that is, the wind is blowing on the top of the projectile, WrE is considered negative. The reverse is true when the wind tends to carry the projectile toward the vertical plane (the wind would now be blowing on the bottom of the projectile), and the WrE is considered positive.

SIGHT ANGLE AND SIGHT DEFLECTION

Thus far we have covered the corrections to the LOF for a stationary elevated target. Bringing the corrections together, the gun is elevated above the LOS by an angle equal to the sum of superelevation, elevation effect of wind, part of the I.V. loss correction, and the elevation spot:

$$Vs = Vf + Vw + Vm + Vj$$

It should be noted here that Vf is based on the gun range, or advance range, to future target position.

The advance range to a stationary air target, corrected for effect of apparent wind, I.V. loss, and range spot, can also be computed at this point:

$$R2 = R + Rw + Rm + Rj$$

From these formulas we see that the effects of wind and I. V. loss enter into sight angle twice, (1) as a correction to range which affects the value of superelevation, and (2) as a direct correction to sight angle.

In addition, the gun must be deflected to one side of the LOS. The deflection angle is given by:

$$Ds = Dw + Df + Dj$$

Ds is measured in the slant plane and is the quantity you set on the gunsight for local control (fig. 10-21). The reason for figuring Ds this way lies in the construction of the once popular yoke-type gun sight. The yoke rotates in deflection about a pivot pin which is perpendicular to the LOS. In other words, the telescope is deflected (traverses) in the slant plane, and Ds is

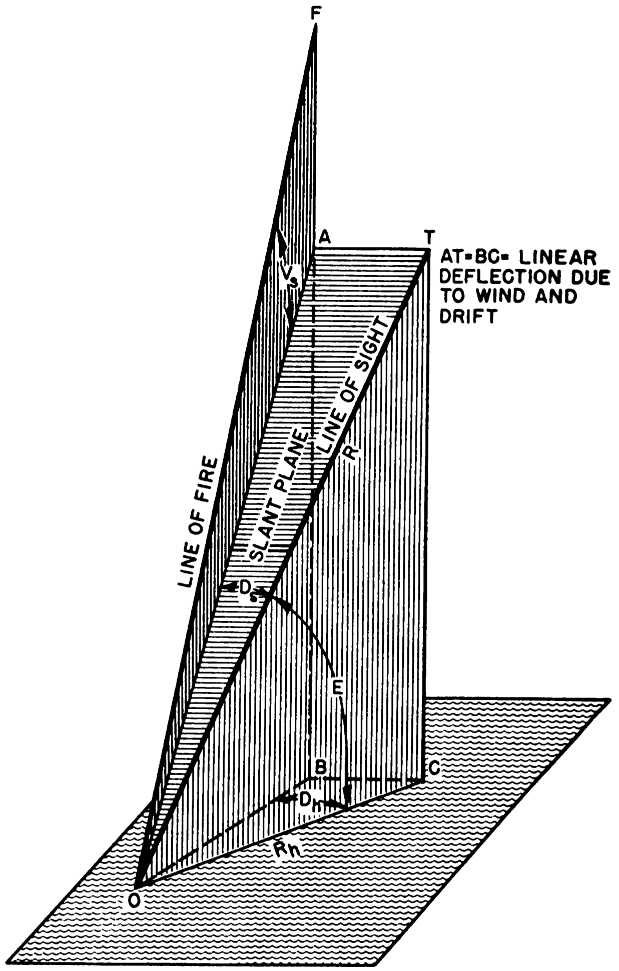


Figure 10-21.—Ds and Dh. 55.727

the angle the sightsetter sets in on the deflection bar of the gunsight.

In figure 10-21, Ds is smaller than Dh, even though BC is equal to AT. This is because R is larger than Rh due to target elevation. Thus, the gunsights are deflected through angle AOT in the slant plane, whereas the mount is trained through the larger angle BOC in the deckplane (assuming the deck to be horizontal). The relationship of these slant plane and horizontal plane angles is quite simply defined in the formula:

$$Dh = Ds \sec E$$

The computer, however, does not use this formula although the principle used is the same. Ds is transferred to the deckplane in the partial-deck-deflection computer while being treated for trunnion tilt—this will be discussed in more detail later. Meanwhile, Ds is transmitted to the gun by synchro for local control.

MISSILE SOLUTION

The present day Navy has put an increasing reliance on the guided missile. There are many and varied types of missiles and missile control systems, each with its own design and method of operation. Consequently, today we deal with a relatively large number of computers. Each computer has its own method of solution. Therefore it is imperative that we look beyond the individual computer's solution and find the common problem. Amazing as it may seem, when looked at objectively, the missile problem and the gun projectile problem are identical. Keep this premise in mind as we solve a basic air problem for a gun projectile.

Before we proceed with the solution, some outstanding points about the missile control problem should be considered. These points will strengthen the idea of the similarity between the missile problem and the gun problem.

After your study of the surface problem, it should be realized that the time of flight of the projectile is the crux of the whole problem. The longer the Tf, the larger will be the predictions. Any error present in the problem would naturally be increased by an increase in Tf. The guided missile's flight, being controlled, eliminates the need for predictions during the guided phase. Therefore the Tf for prediction purposes is small, and any error in the prediction would be extremely small. This is one of the major advantages of the guided missile. However, remember that the basic prediction problem is the same as the gun's prediction problem.

The relative target motion rate is another critical quantity in the missile problem. The rate of movement of the LOS is an indirect measurement of target motion. This information is not only used in the prediction problem, but with a moving air target it also performs a function in the guided portion of the missile's flight. The rate of movement is integrated with time and the generated motion is used to position the guidance element (radar) aboard ship. Therefore the generated rate of movement of the LOS must be smooth and accurate.

From the above you can see that the requirements here are the same for missile and gun. Therefore it is logical to assume that the rates can be computed in a like manner.

MISSILE BALLISTICS

In our discussion of ballistics, we did not consider a particular projectile but spoke in general of the ballistic factors. Here we will follow the same pattern. We will not consider each missile type and its ballistics. But with your knowledge of ballistics and with a little reasoning, you can deduce the effects of the ballistic factors on the individual missile.

Let's first look at the controlled portion of the guided missile's flight. In general, a guided missile is controlled by internal sensing devices and by information supplied from internal or external signals during most of the missile's flight. Once a guided missile is in the controlled portion of its flight, the flight path is corrected continuously. No prediction or separate computation need be made for the ballistic factors. As we make corrections to the missile's flight path for target motion, the ballistic factors are included and therefore compensated for automatically.

Incidentally, this type of solution to the fire control problem is the triangular method. As you may remember, in this method the LOF is made coincident with the LOS.

However, during the initial portion of the guided missile's flight the missile is subject to the effects of the ballistic factors, with no corrections being made. Predictions to compensate for the ballistic factors must be made prior to launch. These predictions are based on the length of time the missile will be in uncontrolled flight. This time factor then would depend on the type of missile, but normally it is a predetermined fixed time period of short duration.

Before going into each ballistic factor, let's compare the guided missile physically to an AA gun projectile. A guided missile is heavy and large as compared to the projectile. At launch the missile's velocity is low. Consequently, a missile's initial momentum is low. (The projectile's initial velocity is high.)

SUPERELEVATION

Gravity acts on all objects in a like manner. Therefore, what was said of superelevation for the gun projectile holds true for the missile. Superelevation correction must be computed and included in the launcher/missile orders. A missile is subject to a relatively large gravational attraction due to its weight. The amount the missile will deviate from its trajectory is due to this attraction and the missile's low initial momentum. However, the deviation due to gravity (Vf) is predicted for only a relatively short time period.

DRIFT

Drift, as we refer to it in the gun projectile problem is caused by the rapid rotation of the projectile. It is normally not necessary for a missile to be rotated rapidly to obtain the same stability. Therefore we need make no prediction for drift correction in the missile problem corresponding to that for gun projectile drift.

CHANGE IN I.V.

This factor is the same in both gun and missile problems. The change in the missile's acceleration is caused by a change in the propellant's temperature from standard. The velocity of the missile obviously governs the distance covered in a given period of time.

WIND

The wind used for prediction is apparent wind. You'll recall that in the surface wind problem the wind tends to carry the projectile with it. This is translatory motion. However, the wind effect on a missile is both translatory and angular. The angular effect is due to the difference in surface area along the missile's length. This difference is mainly due to aerodynamic control surfaces, and is usually largest at the tail of the missile-booster combination. Consequently, the wind tends to turn the missile's head into the wind.

The total predicted wind effect on a missile is small. This is due to the short amount of time used in prediction. In most missile systems, wind correction is not considered.

THE AA RELATIVE MOTION PROBLEM

There are many approaches to the mathematical solution of the AA relative motion problem. However, the following are characteristic of the shipboard long range AA systems. The system is either fully or partially stabilized. The horizontal and vertical planes are the reference planes used in the computer for the solution to the relative motion and prediction problems. Relative motion is resolved into the three coordinates of range, bearing, and elevation, so that linear rates of motion can be established.

The solution discussed here is used in the Computer Mk 1A. Quite naturally it has all the characteristics mentioned above, and since the characteristics are common, the solution (with a little modification) can be applied to other systems.

The AA gun problem is solved to produce three continuous quantities—gun train, gun elevation, and fuze orders. Reduced to simplest form these three answers are diagrammed in figures 10-22, 10-23, and 10-24.

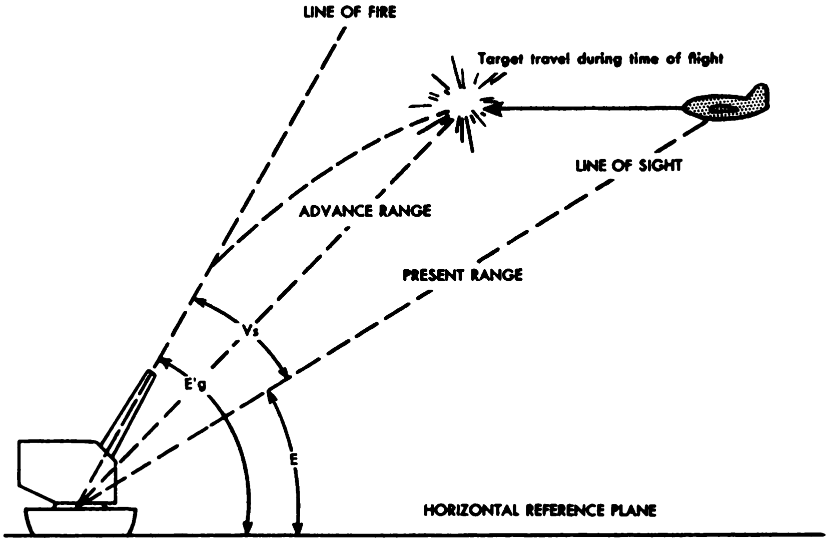
It should be noted that the deck plane is considered to coincide with the horizontal reference plane in these three figures. Locate the following quantities in these first three illustrations and thoroughly study the descriptions for each:

E = TARGET ELEVATION: target elevation above the horizontal reference plane (fig. 10-22).

E'g = GUN ELEVATION ORDER: the elevation of the gun above the deck, measured in a plane through the gun perpendicular to the deck (fig. 10-22).

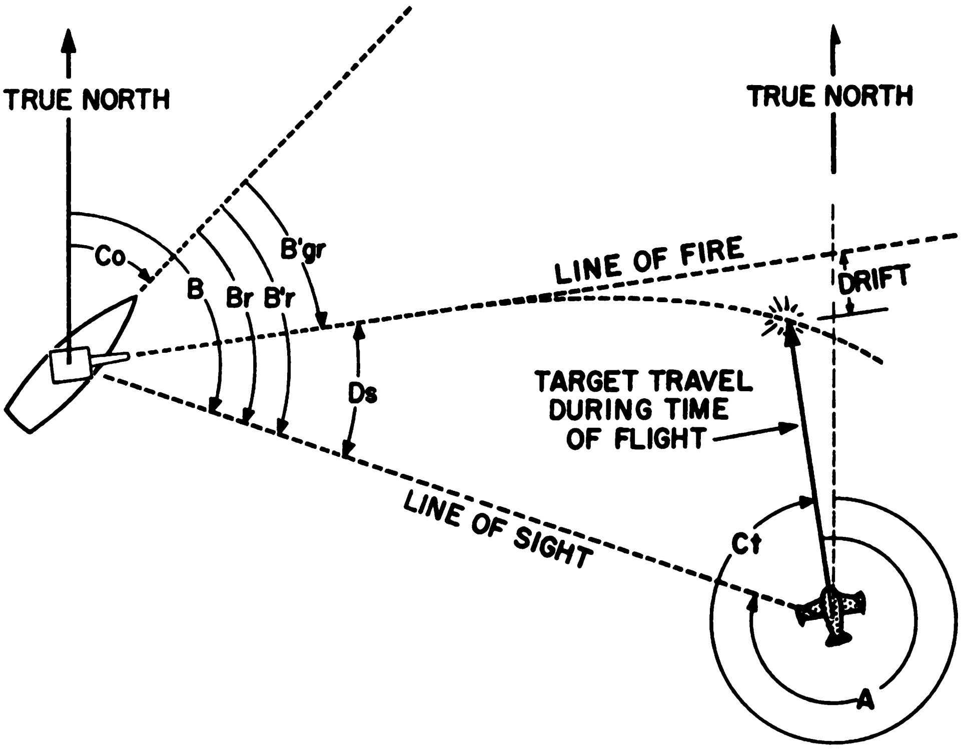
Vs = SIGHT ANGLE: difference between elevation of gun axis above the horizontal plane and elevation of line of sight above the horizontal plane, measured in vertical plane through gun axis (fig. 10-22).

B'gr = GUN TRAIN ORDER: the angle between the fore and aft axis of own ship and the plane through the gun perpendicular to the deck, measured in the deck plane clockwise from the bow (fig. 10-23).


LINE OF FIRE
Target travel during time of flight
LINE OF SIGHT
ADVANCE RANGE
PRESENT RANGE
Vs
E'g
E
HORIZONTAL REFERENCE PLANE

55.228

Figure 10-22.—The basic elements of the AAFC problem contained in gun elevation order.



55.229

Figure 10-23.—The basic elements of the AAFC problem contained in the gun train order.

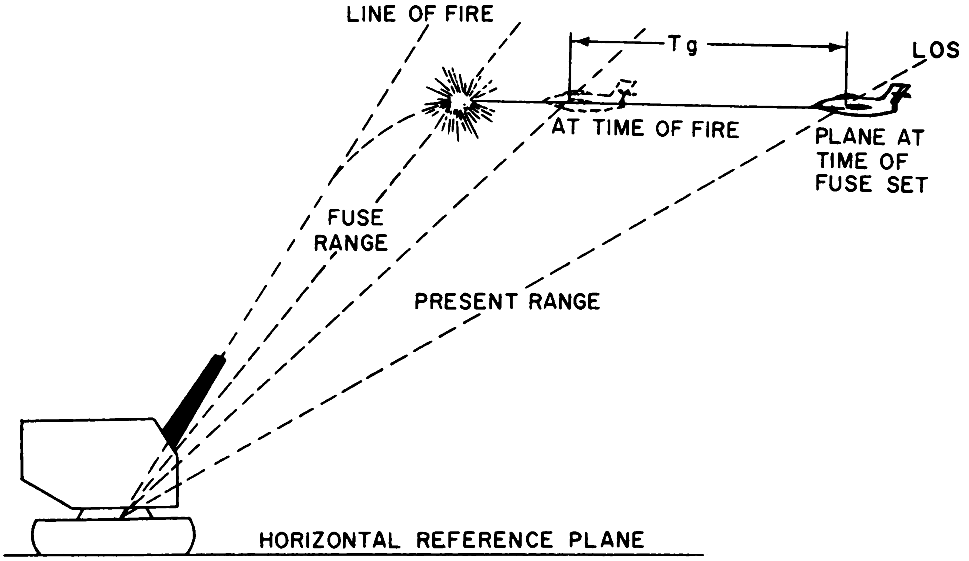


Figure 10-24.—The basic elements of the AAFC problem contained in the fuze order. 55.230

B'r = DIRECTOR TRAIN: the angle between the fore and aft axis of own ship and the vertical plane through the LOS, measured in the deck plane clockwise from the bow (fig. 10-23).

Br = RELATIVE TARGET BEARING: the angle between the vertical plane through the fore and aft axis of own ship and the vertical plane through the line of sight, measured in the horizontal plane clockwise from the bow. As shown in figure 10-23, Br and B'r are equal since the deck plane is assumed to lie in the horizontal reference plane.

B = TRUE TARGET BEARING: the angle between the north-south vertical plane through the LOS, measured in the horizontal plane clockwise from north (fig. 10-23).

(B = Br + Co)

A = TARGET ANGLE: angle between vertical plane through direction of motion of target with respect to earth and vertical plane through line of sight, measured in the horizontal plane clockwise from direction of motion (fig. 10-23).

(A = 180° + B - Ct)

R = PRESENT RANGE: measured along the LOS (fig. 10-24).

R2 = ADVANCE RANGE: predicted range to future target position. (fig. 10-22).

R3 = FUZE RANGE: the range at which the target will be when the projectile now being fired bursts. Fuze range is advance range plus a correction for the time required to load the projectile (fig. 10-24).

Tg = DEAD TIME: the time in seconds between cutting the fuze and firing the projectile. Dead time is illustrated in figure 10-24 by the distance the target has traveled between cutting the fuze and firing the projectile.

Ds = SIGHT DEFLECTION: the angle between the vertical plane through the LOS and the vertical plane through the axis of the gun, measured in a plane perpendicular to the vertical plane through the LOS. Ds is positive if the gun is trained clockwise from the LOS (fig. 10-23).

Ct = TARGET COURSE: the angle between the north-south vertical plane and the vertical plane through the direction of motion of the target with respect to earth, measured in the horizontal plane clockwise from true north (fig. 10-23).

Co = OWN SHIP'S COURSE: the angle between the north-south vertical plane and the vertical plane through the fore and aft axis of own ship, measured in the horizontal plane clockwise from true north (fig. 10-23).

If we make a few preliminary assumptions, the problem will be much easier to solve. If we assume a stable reference plane, zero wind velocity, and the elimination of parallax by locating the director and gun at the same point on the ship, the basic problem becomes that of figure 10-25.

Notice that the problem can now be reduced to (1) the determination of the line of fire, and (2) the calculation of the fuze setting required to burst the projectile at the future position of the target. (Where proximity fuzes are used, the problem reduces to that of determining the line of fire.) We can solve for each part separately. The quantities making up the LOF will be considered first.

PRESENT TARGET POSITION

As in the surface problem the present position of the target is our reference point. It follows then that the first step would be to establish the location of the target relative to own ship. The director measures and transmits to the computer the observed target position. The spherical coordinate system is used. Target's present position is expressed by the three coordinates of range, bearing, and elevation.

RELATIVE MOTION

Relative motion is the change of position of the target as viewed from own ship. This change of position may be the result of target motion only, ship motion only, or a combination of both ship and target motion. Our job, then, is to resolve this relative motion into the three coordinates of range, bearing, and elevation. This can be done by considering the motion of both own ship and target as motion of the target relative to own ship.

By measuring the speed with which the target changes position relative to own ship, we can compute the relative motion rates. A relative motion rate is computed in each of three directions (fig. 10-26) in relation to the LOS:

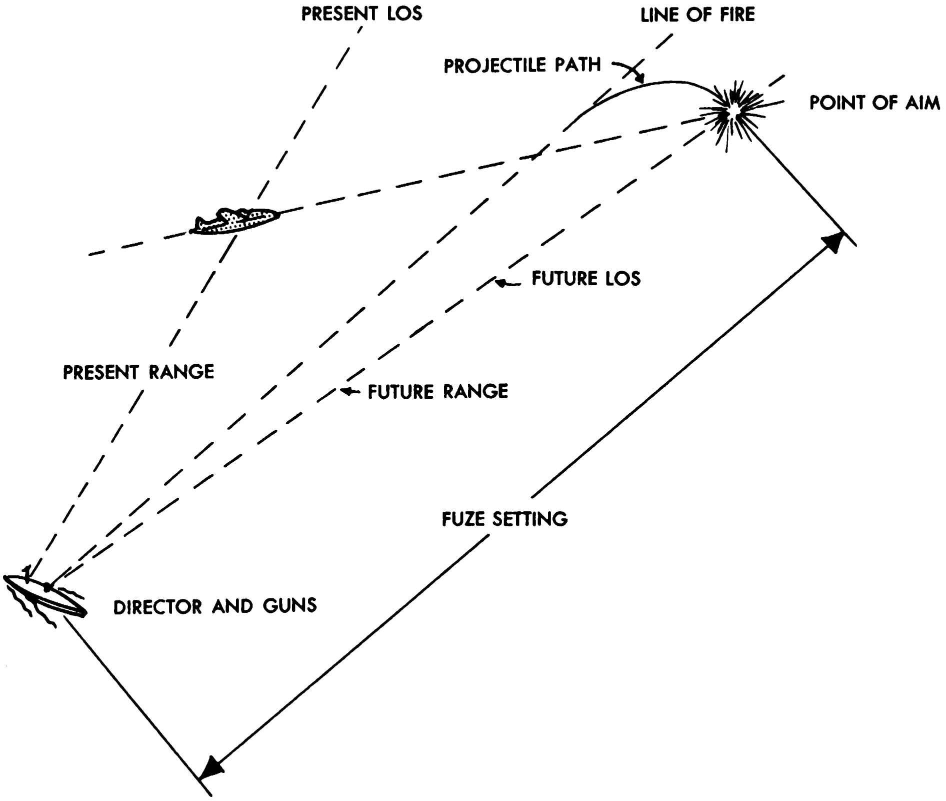


Figure 10-25.—The main components of the AA problem.

55.231

1. Directly along the LOS (direct range rate dR)
2. At right angles to the LOS in the horizontal plane (deflection rate RdBs)
3. At right angles to the LOS in the vertical plane through the LOS (elevation rate RdE)

These three directions are chosen because the resulting rates are in the same axes as the gun mount's motion.

An Elevated Target

An elevated target has three dimensions of motion; therefore, three quantities are needed to define target movement. This is shown in figure 10-27. These quantities are target angle A, target horizontal speed Sh, and target rate of climb dH. Sh is defined as the horizontal ground speed of the air target as projected on the horizontal plane. dH is defined as the vertical speed of the target. It is equivalent to the rate of change of target height, H. It also represents

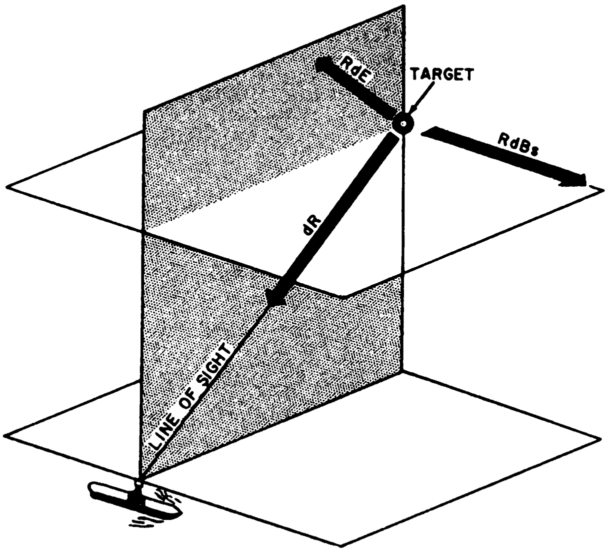


Figure 10-26.—Relative motion rates. 53.111

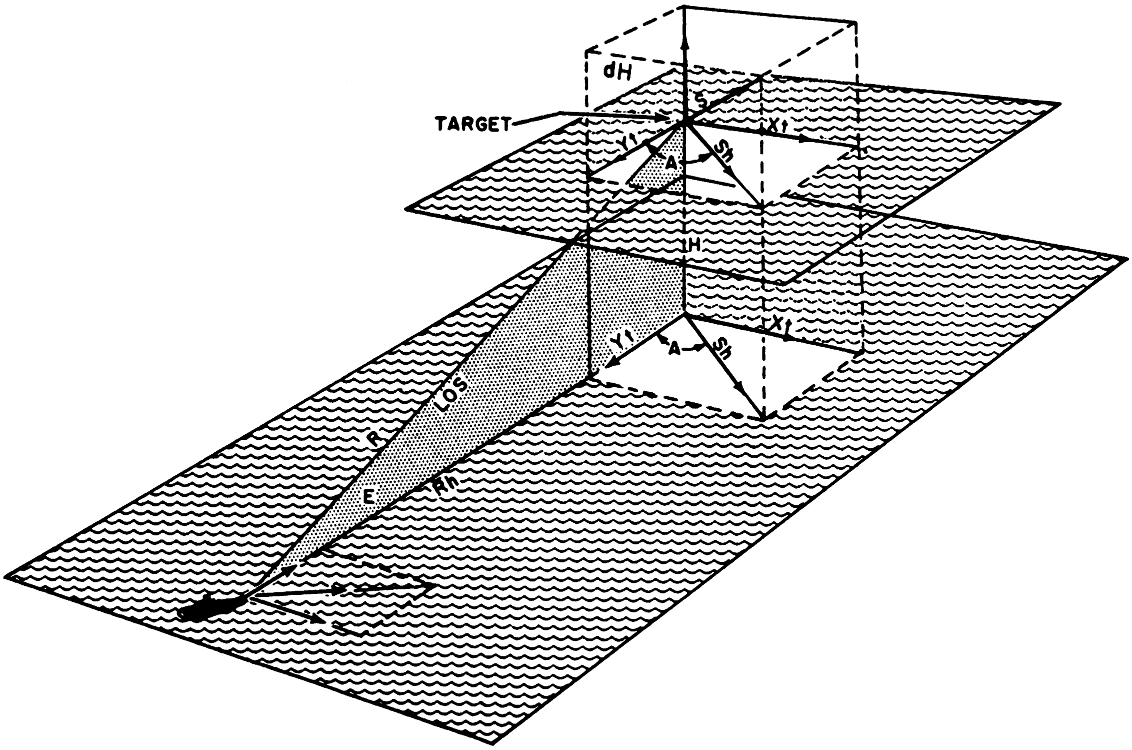


Figure 10-27.—Motion of an elevated target. 52.232

the total vertical relative motion, since own ship moves only in the horizontal.

Notice that Sh and dH are components of the actual airspeed of the target S. They indirectly define the inclination of target motion to the horizontal.

A Surface Target

If we assume target elevation to be zero, as with a surface target, the vector resolution of own ship and target horizontal motion becomes that shown in figure 10-28. This, you will recall, is the same method employed in the surface problem where:

Xo (Deflection component of own ship velocity) = So sin Br
Yo (Range component of own ship velocity) = So cos Br
Xt (Deflection component of target velocity) = Sh sin A
Yt (Range component of target velocity) = Sh cos A

If we combine the Y components, as shown in figure 10-28, the result will be the horizontal range rate component of relative target motion called dRh. Likewise, when the X components are added we obtain a component across the LOS called linear deflection rate RdBs.

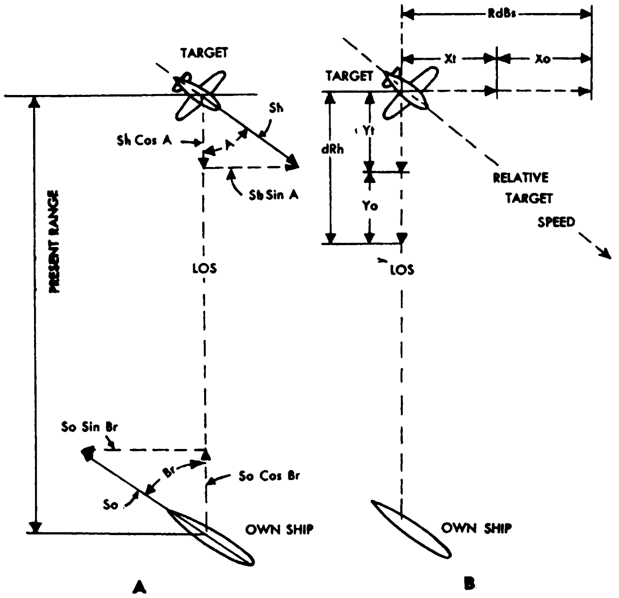


Figure 10-28.—Motion can be considered to be relative. 55.233

Both dRh and RdBs are relative motion quantities. We can say, therefore, that the target in figure 10-28 is moving at an apparent rate which is the sum of both own ship and target motion in the horizontal plane.

The two Y components show you how fast the horizontal range rate dRh, measured from own ship to the point directly under the target, is changing. Their sum is the total rate of change of horizontal range. That is:

$$dRh = Yo + Yt.$$

The only components that have any tendency to change the bearing of the target are the X components. Therefore, the linear bearing rate is given by the formula

$$RdBs = Xo + Xt.$$

The three vectors dH, dRh, and RdBs form true rectangular coordinates of a single vector representing the relative speed between own ship and target. This is shown in figure 10-29.

Notice, from figure 10-27 that the vertical height of the target above the horizontal through own ship is obtained by multiplying the slant range R by the sine of E. Thus:

$$H \text{ (Feet)} = R \text{ (yards)} \times 3 \times \sin E$$

The horizontal range to a point directly beneath the target is the cos E component of R. Thus, we can write:

$$Rh = R \cos E$$

LINEAR RATES

The linear rates dRh, dH, and RdBs are the result of our original selection of the components of target movement. These linear rates, however, do not entirely correspond with the three degrees of movement of the Mk 37 director. The director has three degrees of freedom—range, bearing, and elevation. Thus, the director can measure only changes in range along the LOS, changes in target elevation perpendicular to the LOS in the vertical plane containing the LOS, and changes in target bearing at right angles to the LOS in the horizontal plane.

Fortunately, RdBs can be used without modification since it can be projected onto the horizontal plane, as shown in figure 10-29, and is computed at right angles to the LOS. We must, however, calculate the linear rate of change of

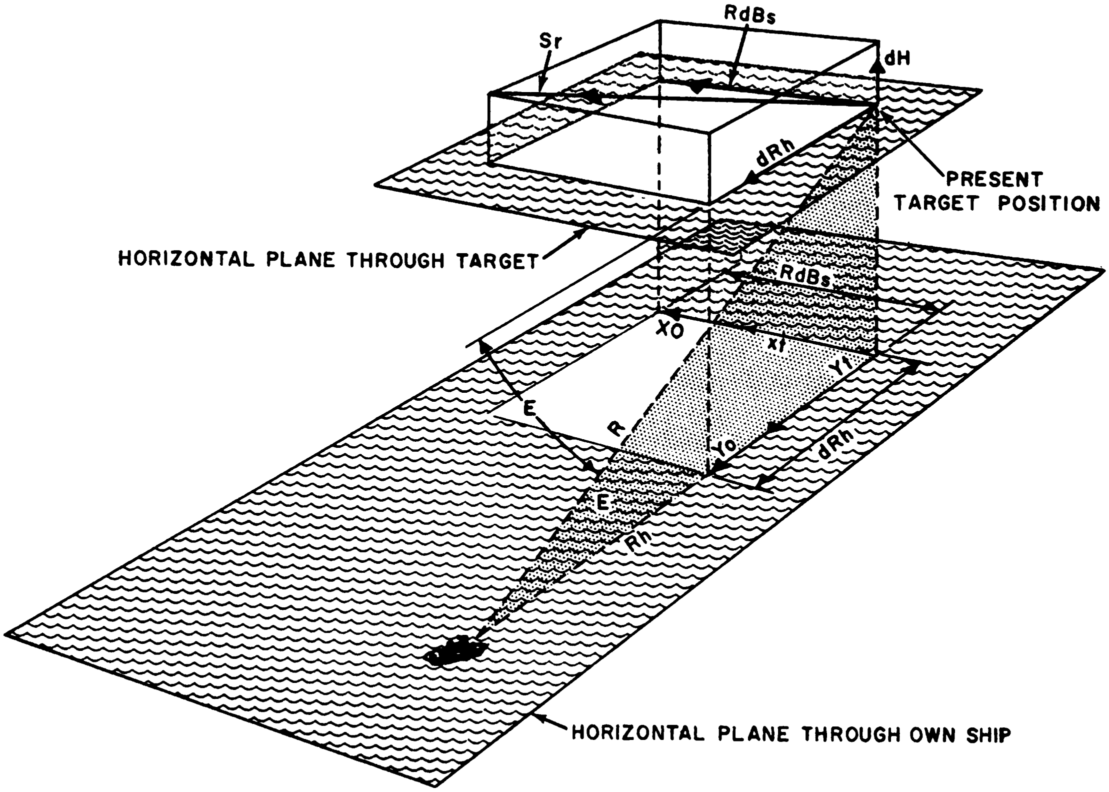

RdBs
Sr
dH
dRh
PRESENT TARGET POSITION
HORIZONTAL PLANE THROUGH TARGET
RdBs
XO
Xt
Yt
E
R
Yo
dRh
E
Rh
HORIZONTAL PLANE THROUGH OWN SHIP

Figure 10-29.—Relative motion of an aerial target. 55.234

slant range, and the linear rate of change of elevation perpendicular to the LOS. Both of these quantities are measured in the vertical plane containing the LOS. Figure 10-30 illustrates the two components of relative speed which affect slant range rate; they are dRh and dH. (Notice that RdBs has no component along the LOS and therefore has no effect on slant range rate.) It is clear, in this case, the dRh is tending to shorten the range, while dH is tending to lengthen it. You can see from figure 10-30 that slant range rate

$$dR = dRh \cos E + dH \sin E$$

In figure 10-30 dRh is negative, so dR is equal to the difference of the two components. The quantities required can be obtained from a pair of component solvers.

Notice, also, that the components of dRh and dH perpendicular to the LOS are tending to increase target elevation. This means that if the target plane climbs, the elevation angle increases. E also increases if the target plane

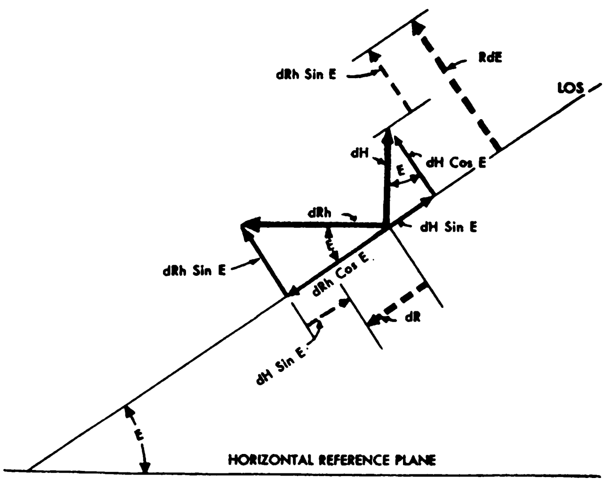


Figure 10-30.—Direct range rate and linear elevation rate. 55.235

comes nearer, keeping the same height. Since RdBs, the other component of S, has no component in the vertical plane, the linear elevation rate is given by

$$RdE = dRh \sin E + dH \cos E$$

The calculation of RdE and dR completes the resolution of the mutually perpendicular components of motion around the LOS. See figure 10-31. RdBs can be projected onto the horizontal reference plane containing own ship without alteration.

These components—dR, RdBs, and RdE—form the basis for the generated rates and predictions, and they are the final output of the linear-rate section of the Mk 1A computer. They are the final output of the own-ship and target component-solver group, and each appears as a servo shaft position.

Figure 10-31 is a schematic diagram showing how the linear rates are computed with four component solvers and a group of differentials. Trace out the entire diagram, and refer to the mathematical expressions shown in figures 10-27, 10-28, 10-29 and 10-30. All the inputs appear on the left, whereas the three outputs appear at the right of figure 10-31. Notice particularly that RdBs is made up just as it was in the surface problem; it is the direct addition of the own-ship and target X-components. The RdBs servo motor merely increases the power sufficiently to drive other computer components. The same applies for the dR and RdE servos. Also notice that dRh from the own-ship and target component solvers is the speed input to the dRh component solver, after being amplified by a servo. As previously mentioned, dH and dRh affect both slant range rate and linear elevation rate.

GENERATING MECHANISMS

Three steps are required if accurate values of gun train, gun elevation, and fuze setting are to be continuously and accurately computed: (1) checking and correcting the estimates of target movement, (2) maintaining a reliable figure at all times for the present value of target range, bearing and elevation, and (3) computing repeatedly the range, bearing, and elevation of the future position of the target—the place it will be when the shell reaches it. The first two steps are performed by the generating mechanism of a computer, the third by the prediction mechanism.

Starting with some known position of the target, the generating mechanism uses the estimated speed and direction of target movement to calculate continuous GENERATED values of present range, bearing and elevation. These generated values are correct only if the estimate of target movement is correct. Therefore, comparison of the generated values with observed values provides a check on the correctness of the estimates.

The size of any errors observed tells you what changes to make in your original estimates.

Thus, by a process of trial and error, accurate values of target movement can be determined. When this is accomplished, a solution is obtained and generated values can be used in place of the observed values if the target is momentarily obscured. More important, you now have accurate information on which to base your PREDICTION of future target position.

The basic method by which AA computers compute generated values is the same as that used in surface fire machines. The RATE at which each of the three quantities—range, bearing, and elevation—is changing at every instant is computed and set up on an integrator.

The integrator is essentially a variable speed transmission. Its output shaft rotates at a speed proportional to the rate at which range, for example, is changing. Therefore, if the output shaft drives a dial or counter which was originally set at the correct value of range, the dial will continue to read a correct value, provided the target continues on the same course at the same speed.

GENERATED RANGE

We have already computed dR (direct range rate) along the line of sight. Increments of generated range ΔcR, can be computed by the formula:

$$\Delta cR = dR \times 1936 \times T$$

Now, if ΔcR is added to a measured value of present range, the result will be cR, generated present range in the slant plane containing the line of sight. This computation is performed by an integrator. The carriage is positioned by dR, and a time motor turns the disk at a constant speed. The output, ΔcR, is added to R in a differential to furnish generated present range, cR (fig. 10-32).

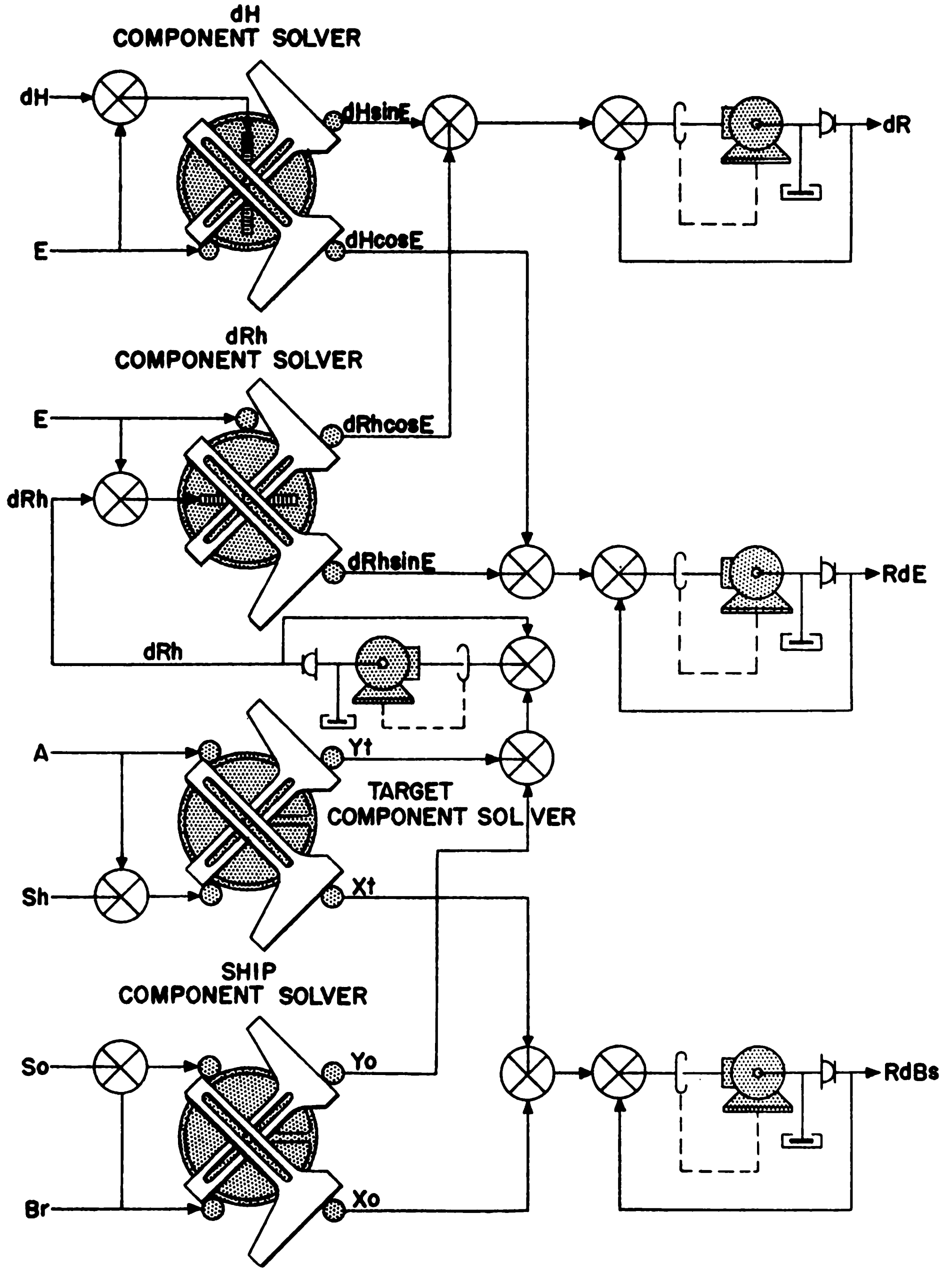


Figure 10-31.—Computation of linear rates.

55.236

GENERATED RELATIVE TARGET BEARING

We know that RdBs is a linear motion tangent to circles of radius $\frac{R}{1000}$, and radius Rh, and it is measured in the slant plane containing the LOS. If we divide RdBs, in yards per second, by R, the answer will be angular bearing rate, dBs, in the SLANT PLANE in mils per second.

Since we have assumed that the deck plane lies in the horizontal reference plane, we can call the slant plane the TRAVERSE plane. The traverse plane is defined as the slant plane containing the line of sight and the sight trunnions.

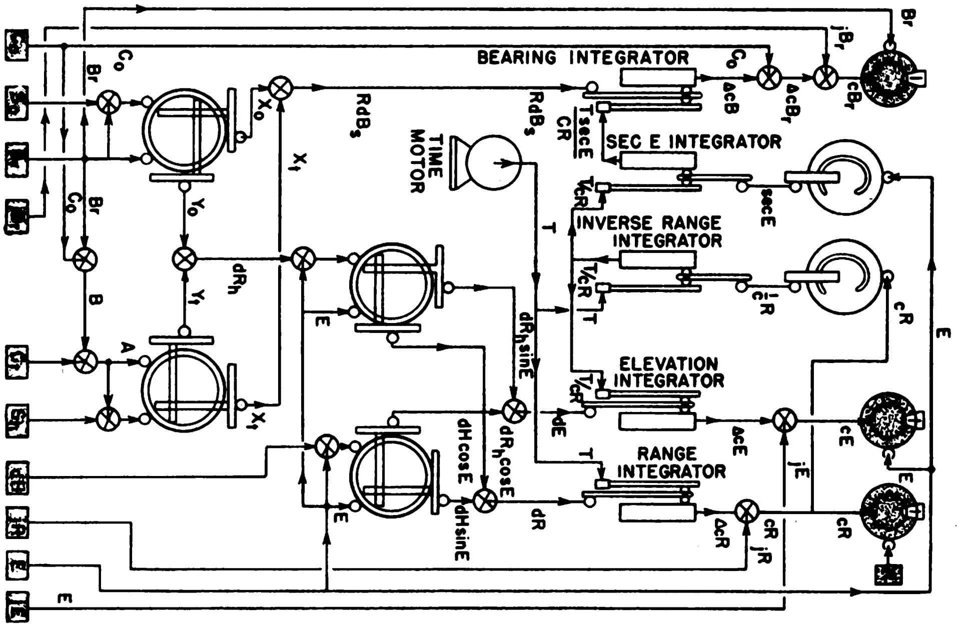


Figure 10-32.—An AA generating mechanism. 55.237

If the ship rolls, the sight trunnions roll; therefore, the traverse plane also rolls. Only when roll and pitch are zero does the traverse plane correspond with the slant plane containing the LOS and RdBs.

But, since the director telescopes and the guns are not built so they can traverse, they train in azimuth. The angular bearing rate, therefore, must be calculated in the HORIZONTAL PLANE.

This means RdBs must be divided by Rh instead of R to get dBs in the horizontal plane. We know that Rh = R cos E; therefore

$$\text{Angular bearing rate} = \text{RdBs} \times 1936 \times \frac{1}{\text{R cos E}}$$

(The constant, 1936, is used to convert knots to minutes of arc per second of time.)

Since we need continuous values of range, cR is substituted for R. Now if this angular bearing rate is multiplied by time, we will have increments of generated true target bearing in mils.

$$\Delta\,\text{cB} = \text{RdBs} \times 1936 \times \frac{1}{\text{cR}} \times \frac{1}{\cos \text{E}} \times \text{T}$$

Δ cB, increments of generated true target bearing, can be computed by means of two cams and three integrators (fig. 10-33). The output of an inverse range cam controls the carriage of an inverse range integrator. The disk of the integrator is driven at constant speed by the time motor, so the output roller turns at a speed proportional to T/cR. T/cR drives the disk of a second integrator whose carriage is positioned by the output of a cam which is proportional to 1/cos E. In trigonometry, 1/cos E is equal to the secant E. This cam, therefore, is called the sec E cam. Likewise, the second integrator is called the sec E integrator.

The output roller of the sec E integrator drives the disk of the bearing integrator at a speed proportional to T/cR x sec E. The carriage of the bearing integrator is set by RdBs. Hence the speed of the output is dBs sec E, and the change in generated bearing Δ cB is the total turns of the output roller. Thus:

$$\Delta\,\text{cB} = \text{RdBs} \times 1936 \times \sec \text{E} \times \frac{\text{T}}{\text{cR}}$$

Own ship course, Co, is combined with Δ cB in order to get change in relative bearing, ΔcBr.

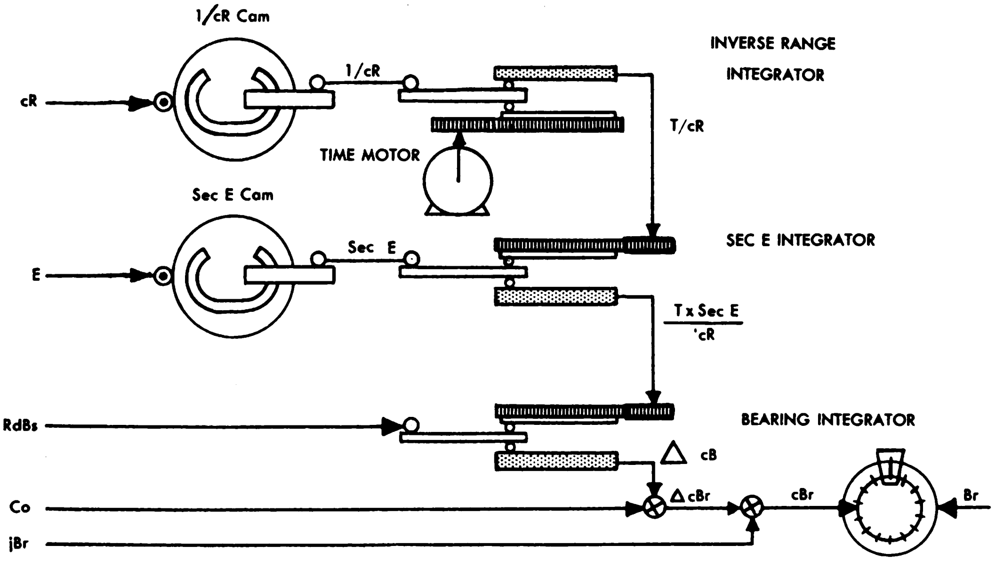


Figure 10-33.—Generated relative target bearing. 55.238

Now if this quantity is added to the initial measured value of relative bearing, jBr, the answer is generated relative bearing. Thus:

$$cBr = \Delta cB + Co + jBr$$

GENERATED ELEVATION

Angular elevation rate is the linear rate, RdE, divided by SLANT RANGE. So, generated elevation is obtained by using RdE to set the carriage of the elevation integrator (fig. 10-32) whose disk is driven by the output of the inverse range integrator, $\frac{T}{cR}$ Therefore, increments of generated elevation are computed from the formula

$$\Delta cE = RdE \times 1936 \times \frac{T}{cR}$$

ΔcE is added to the initial value of elevation in a differential to give cE, generated target elevation.

Figure 10-32 is a schematic of the generating mechanism for the Mk 1A computer used with the Mk 37 GFCS. By now you are familiar with schematics and shouldn't have any difficulty tracing the outputs of cE, cR, and cBr from the inputs of own ship and target course and speed.

PREDICTING TARGET POSITION

The remaining problem in dealing with target motion is to predict the range, bearing, and elevation of the point which the target will occupy when the projectile arrives. Referring again to figure 10-25, we see that this is the point of aim.

Now that we have established the three linear rates dR, RdBs, and RdE (fig. 10-31), the predictions are not difficult. To find the future position of the target each rate is multipled by the Tf:

Relative motion range prediction, $Rt = dR \times Tf$

Relative motion deflection prediction, $Dt = RdBs \times Tf$

Relative motion elevation prediction, $Vt = RdE \times Tf$

The fact that the rates dR, RdBs, and RdE contain components of own ship's motion has undoubtedly occured to you. The question naturally arises: Why include own ship's motion in the prediction? Has not the projectile left the ship? The answer is that own ship's motion is imparted to the projectile, and therefore must be included in the predictions.

The three prediction components are illustrated in figure 10-34. Now your problem is to find the advance range (R2) and the future elevation (E2) of the future target position (T2). Also you need the deflection prediction angle (Dt) measured in the slant plane between the

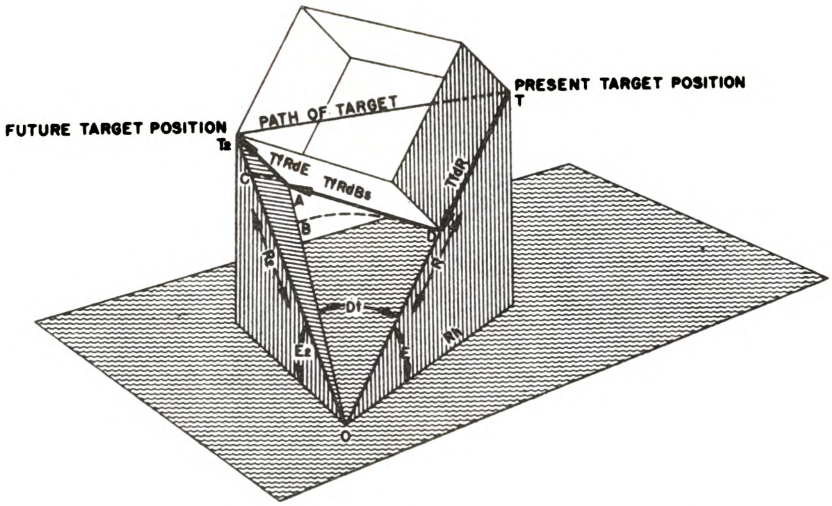


Figure 10-34.—Components of relative motion during Tf. 55.239

vertical planes, and through the lines of sight to present and future target positions.

The range prediction must be corrected for the effect of elevation and deflection prediction (figs. 10-35 and 10-36), while the elevation prediction must be corrected for the effect of the deflection prediction. When these corrections are made, accurate values of R2 and E2 are obtained. The formulas used to arrive at E2 and R2 are complex and contain approximations. You are not required to know the mathematics involved. But you should understand the nature of the errors and their corrections. The formulas are included to indicate these corrections.

DEFLECTION PREDICTION

The angle marked Dt in figure 10-34 is not quite correct. It is measured from the vertical plane through the present LOS to a slightly slanting plane (OT2A) through the future target position. But it is a close approximation and is the angle that is used. Figure 10-34 greatly exaggerates the slant of plane OT2A, so the actual discrepancy is not large.

Angle Dt, in mils, then equals $\frac{AD \times 1000}{OD}$.

Since OD is nearly equal to R2, we can write:

$$Dt = \frac{TfRdBs}{R2} \times 563 = RdBs \times \frac{Tf}{R2} \times 563$$

RANGE PREDICTION

It is obvious from figure 10-34 that most of the change in range results from the range component, TfdR. The largest part of the range prediction, therefore, is Rt. However, R2 is larger than OD. One of the contributing factors is that the length of CO (which equals AO) is larger than OD by the distance AB. This is caused by the deflection prediction, TfRdBs. The compensation for the error, Rx, has been found to be closely proportional to the product of KTf, or R2, and the square of the rate, RdBs. The formula is:

$$Rx = KTf(RdBs)^2$$

Referring to figure 10-34 again, you can see that R2 is greater than CO by the small distance, CT2. This range effect of elevation is called Re and is computed in exactly the same way as R_x; therefore:

$$Re = KTf(RdE)^2$$

Thus, the total range prediction is:

$$Rtxe = Tf \times \left[dR + K(RdBs)^2 + K(RdE)^2\right]$$

Our final calculation is the change in elevation caused by the target moving from T to T2, that is, to find the elevation prediction. Just as in the case of the deflection prediction, the computation is based on an approximation. The same approximation is used where it is assumed that plane OT2A lies very nearly in the vertical plane through line OT2 (fig. 10-34).

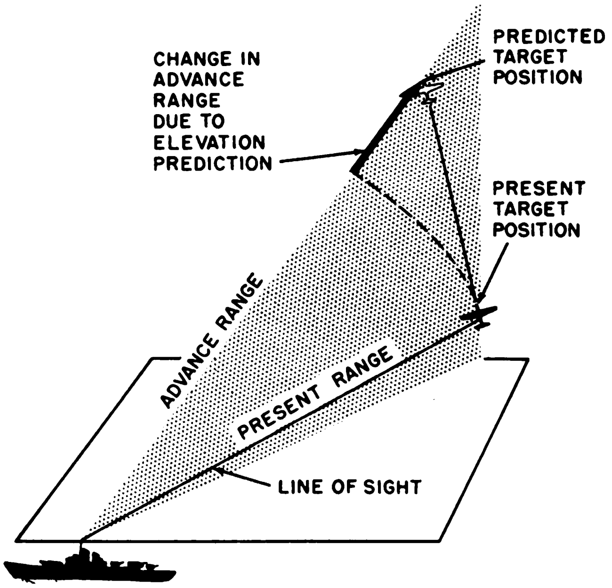

CHANGE IN ADVANCE RANGE DUE TO ELEVATION PREDICTION
PREDICTED TARGET POSITION
PRESENT TARGET POSITION
ADVANCE RANGE
PRESENT RANGE
LINE OF SIGHT

Figure 10-35.—How target elevation affects advance range. 55.240

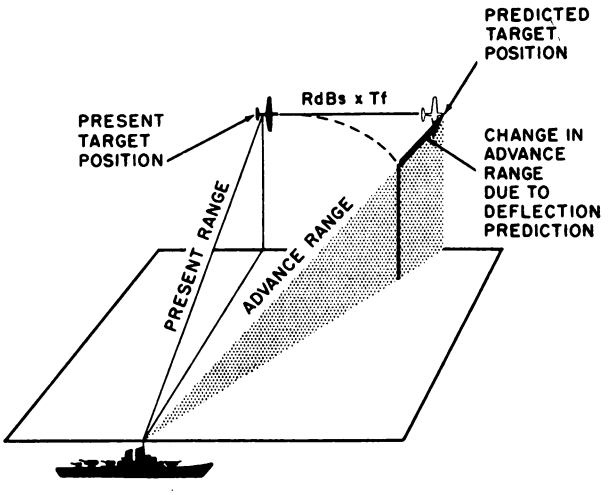

PREDICTED TARGET POSITION
RdBs x Tf
PRESENT TARGET POSITION
CHANGE IN ADVANCE RANGE DUE TO DEFLECTION PREDICTION
PRESENT RANGE
ADVANCE RANGE

Figure 10-36.—How target deflection affects advance range. 55.241

Here you assume that the elevation of the future line of sight, OT2, is simply the elevation of line OA plus the angle AOT2. The angle AOT2 is the biggest part of the elevation prediction. You can see from figure 10-34 that angle AOT2 equals TfRdE/R2. This is called Vt.

The remainder of the prediction, called the COMPLEMENTARY ERROR, is the difference in elevation between line OA and the present LOS, OT. Actually there is no change in height in moving from point D to point A. But remember that the deflection component causes an increase in range equal to AB in figure 10-34. This increase equals $R2(Dt)^2/2$. When a target moves away from you, without changing its height, its elevation decreases. The complementary error is the amount of this change in elevation.

Figure 10-37 shows you how the complementary error is calculated. Here point D has an elevation E and some definite height H. Point A has the same height, but its range is greater by an amount $R2(Dt)^2/2$. The difference in elevation of the two points is the complementary error.

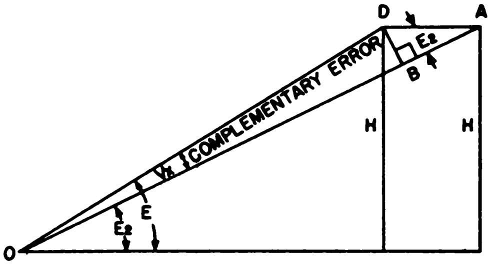


Figure 10-37.—Complementary error. 55.242

You can see that distance AB (fig. 10-37) is nearly equal to the difference in range. Therefore, distance DB equals

$$\frac{R2(Dt)^2}{2} \text{ x tan E2}$$

The complementary error angle, Vx equals $\frac{DB}{R2}$

therefore: $Vx = \frac{R2(Dt)^2}{2}$ x tan E2 divided by R2,

the R2's cancel leaving: Vx (Dt)2x1/2 tan E2.

SIGHTSETTING

You have now learned all the factors that enter into sight deflection, sight angle, and advance range. Thus, you have arrived at the general formula for sightsetting against an air target:

$$Ds = dt + Df + Dw + Dj$$

$$Vs = Vf + Vt + Vw + Vj$$

Remember that superelevation Vf is based on advance range R2, which is calculated by

$$R2 = R + Rtxe + Rw + Rm + Rj$$

and on advance elevation E2, which is calculated by

$$E2 = E + Vf + Vw + Vx + Vt$$

FUZE SETTING

Unless proximity fuzes are used, antiaircraft guns usually employ time-fuzed projectiles equipped with clockwork fuzes adjusted to explode the shell at a set time after it is fired. This is done because the chance of a direct hit on an aircraft is rather slight; but, if the projectile can be made to burst as it passes near the plane, blast and flying fragments may do almost as much damage as a direct hit.

Therefore, in addition to knowing the sight settings, knowledge of the proper time interval to set on the fuze is necessary.

If the fuze could be set at the instant the projectile is fired, you could use time of flight Tf. Actually, however, the fuze is set while it is the projectile hoist on its way up from the handling room. After the setting is made, the projectile is lifted on the tray, rammed home, and the breech closed before the projectile is fired. All this takes several seconds, depending on the speed of the gun crew. This time interval is called dead time, and is represented by the symbol Tg.

During the dead time the range to the target is changing; therefore, at the instant the projectile is fired, the range and the time of flight are different from the value computed at the instant the fuze was set.

Consequently, when the fuze is set, you cannot use the value of Tf indicated on the computer. It is necessary to use a different time of flight called F, corresponding to fuze range R3.

In the computer, fuze range (R3) is determined by computing the change in advance range during dead time RTg and then adding RTg to the current value of R2. Thus,

$$R3 = R2 + RTg$$

It should be noted here that, as range changes during time of flight, and the difference in the amount of this change during Tg must be accounted for, the value of RTg derived in the computer includes a compensating factor for this difference.

The multiplication is performed in the DEAD TIME MULTIPLIER and is added to R2 in a differential.

Fuze setting F is obtained from the fuze ballistic computer which is driven by R3 and E2. Theoretically, the elevation input should be E3, corrected for change of elevation during dead time, but E2 is considered accurate enough.

CHAPTER 11

GUN ORDERS

SOLVING THE FIRE CONTROL PROBLEM

It is easy to overemphasize certain equipment by not fully appreciating how it fits into the complete system. A gun fire control system is comprised of a group of instruments working together to produce gun orders. An overview of the problem's solution, and an understanding of the flow of information, will show the importance of ALL the equipment.

Although the steps involved in the solution of the problem of hitting a moving target from a moving ship are many, they can be summarized as follows:

1. Determine present target position in relation to own ship.
2. Predict future target position in relation to own ship.
3. Stabilize the various units.
4. Calculate required corrections to gun orders.
5. Transmit data to guns.

We will use the makeup of gun orders to see the contribution of each instrument to the solution. The differences between surface and air targets will be explained as we review the steps. Since the instruments in the systems are interdependent, and work simultaneously, the steps may overlap.

STEP 1—DETERMINE PRESENT TARGET POSITION

STEP 1 of the problem is performed by the director. The director's primary function is to locate and track the target by means of either radar or optical equipment. Thus the director establishes the LOS which is the basic reference line.

To establish the target's present position, a surface director measures target range and bearing. The target's bearing in the deck plane is measured by director train. B'r' is transmitted to the rangekeeper and the stable vertical, so that the LOS can be established in these instruments. Range is transmitted to the rangekeeper.

Director elevation E'b is measured by the director in a plane perpendicular to the deck plane, through the LOS. However, in surface fire, where the LOS is always considered horizontal, E'b is normally measured by the stable vertical.

The situation in AA fire is more complicated. To define target's position, the director must continuously make three simultaneous measurements: range, director train, and director elevation. To facilitate making these measurements, the director's LOS is stabilized. A crosslevel input to the director's telescopes and radar antenna keeps the elevation axis of rotation parallel to the horizontal plane (fig. 11-1). Consequently the director's LOS elevates in a vertical plane perpendicular to the horizontal.

You remember that the pointer's or leveler's telescope in a surface director elevates in the same manner as the guns. That is, the elevation prism of the telescope turns about trunnions which are always parallel to the deck. The LOS elevates in a plane perpendicular to the deck. In surface fire, where the LOS is always horizontal, this causes no trouble. However, let's consider the action of this sight if it is used on an elevated target.

Imagine that the deck is level. The director trains from the bow of the ship around to a point vertically under the target. Then the telescope elevates vertically to the target. But now suppose that the ship rolls so that the gun and telescope trunnions are tilted. The telescope LOS will swing far to one side. In order to get back on target, the trainer will have to train the director to a point perpendicularly under the target. As the ship reverses its roll, he will have to train back. The value of director train will be changing continually as the trunnions tilt.

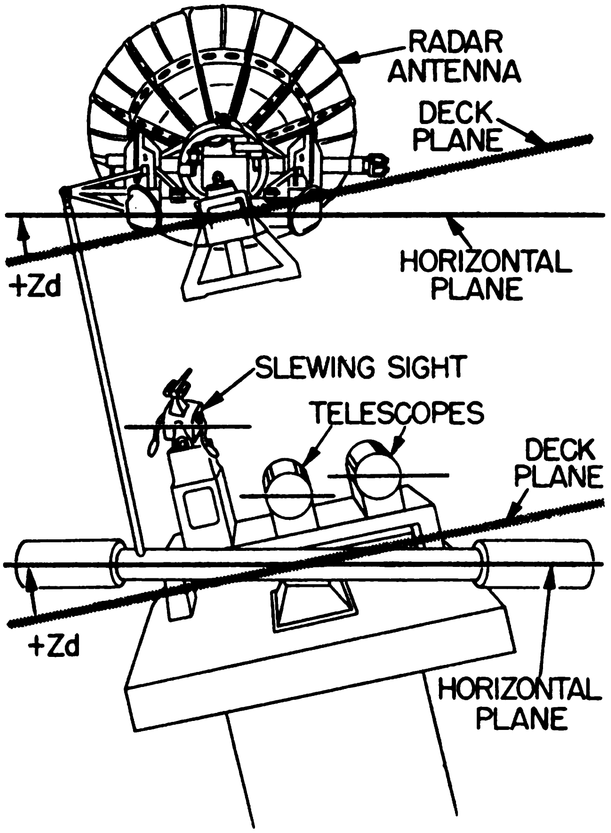


Figure 11-1.—Stabilization of LOS keeps elevation axes of director optics and radar antenna in the horizontal plane. 55.243

The spherical diagram (fig. 11-2) shows you the basic difficulty. You are measuring the angle (B'r') in the deck plane, between the centerline of the ship and a plane through the LOS perpendicular to the deck. As the tilt of the deck changes, this plane keeps moving—and the value of director train changes as it moves.

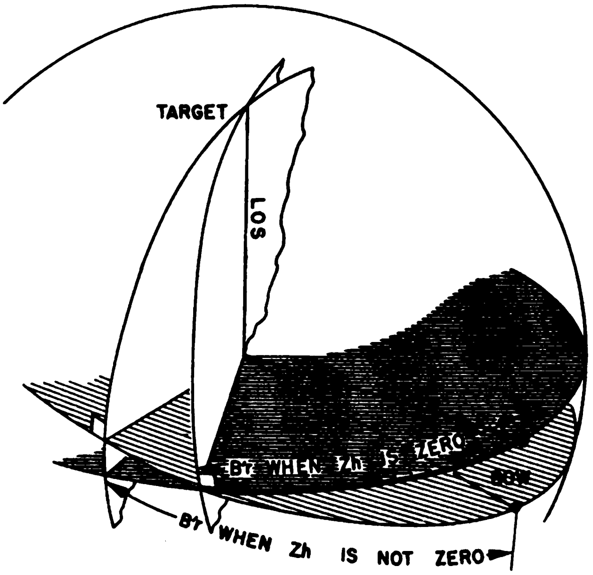


Figure 11-2.—Angles measured by a director which is not stabilized. 55.244

This difficulty is avoided, however, in the design of an AA director such as the Mk 37. The telescopes are mounted so that they may be rolled on bearings about their own axis within the telescope housing. An input of crosslevel from the stable element turns each telescope, keeping the prism trunnions horizontal at all times. Thus the telescope LOS elevates and depresses in a vertical plane through the target, regardless of how the ship rolls. As a result, director train is always measured from the bow of the ship to one particular plane—the vertical plane through the LOS to the target. This value of director train is called B'r instead of B'r'. It is true, however, that changes in crosslevel will still make a small difference in the value of director train, because director train is measured in the deck plane, and the deck plane moves as crosslevel changes. But large changes in train are prevented by stabilizing the director.

Figure 11-3 shows the outside of the telecope and its housing, as well as a schematic view of the way it operates. Notice particularly how the elevation input works. The elevation gearing drives an idler ring gear which, in turn, drives the gearing to the prism. This raises another design problem. Changes in crosslevel will introduce false inputs of elevation. For, as the telescope rotates, the gearing from the idler gear to the prism will walk around the ring, rotating as it does so. The gearing ratios are such that the false elevation input, caused by the effect of crosslevel, can be removed by subtracting one-thirtieth of crosslevel from the elevation input.

Stabilizing the director has one other important advantage. It gives you a direct measured value of target elevation E. Target elevation is the angle, measured in a vertical plane, between the LOS and the horizontal. With a stabilized director, director elevation Eb is the angle measured in a vertical plane between the LOS and the deck. Thus the only difference between E and Eb is the angle between the deck and the horizontal-level angle, L. Therefore:

$$Eb = E + L$$

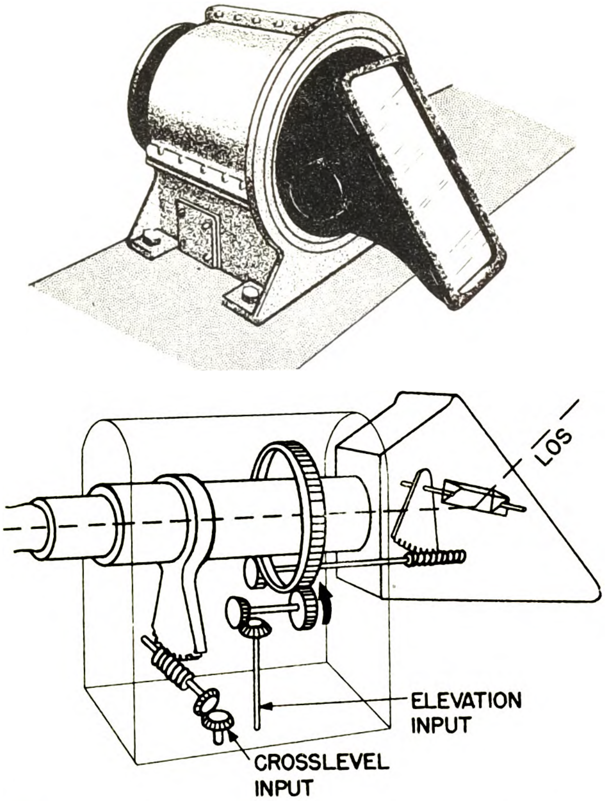


Figure 11-3.—Telescope used in a stabilized director. 55.245

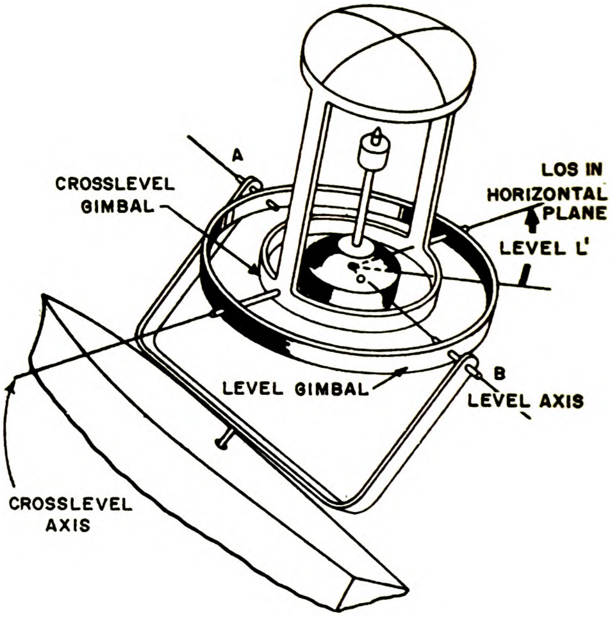


Figure 11-4.—The stable vertical. 55.246

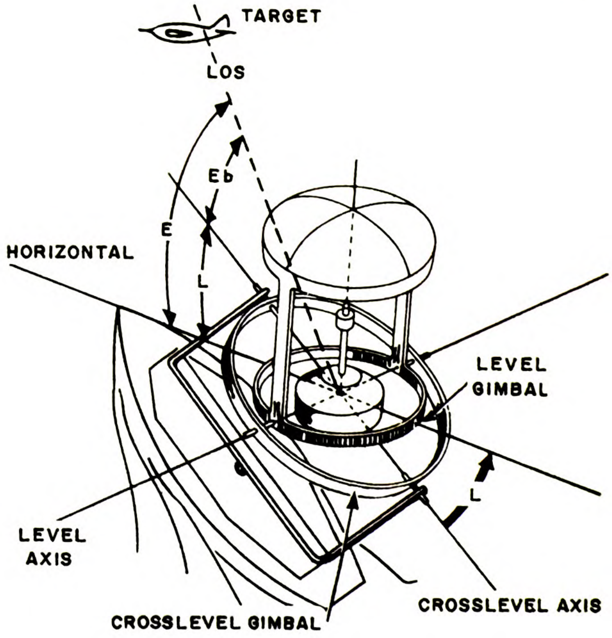


Figure 11-5.—The stable element. 55.247

Since E and Eb are angles in a vertical plane, L must be measured in the same vertical plane. The stable vertical used in surface fire, you remember, measures level L' in the plane perpendicular to the deck. Figure 11-4 shows why this is so. The outer gimbal of the stable vertical has its axis at right angles to the LOS. Movement of this gimbal, therefore, measures level angle. And since the outer gimbal axis is always parallel to the deck, it measures level in the plane perpendicular to the deck. The inner gimbal, which measures crosslevel, always has its axis horizontal because it is attached to the outer gimbal which is kept horizontal by the level followup.

If the senstive element is turned 90° from its position in figure 11-4, the axis of the outer gimbal will be headed along the LOS as in figure 11-5. Thus the outer gimbal measures crosslevel in the deck plane and, at the same time, keeps the axis of the inner gimbal horizontal. The inner gimbal, therefore, measures level in a vertical plane. This value of level is called L instead of L'.

A stabilizing unit designed to measure level with its inner gimbal is called a stable element. The angles measured by the stable element are illustrated in the spherical diagram of figure 11-6. Notice that L is measured in the vertical plane containing the LOS. Zd is the angle of roll about the line which is the intersection of the deck plane with the vertical plane through the LOS.

STEP 2—PREDICT FUTURE TARGET POSITION

The future position of the target is calculated in the computer. The future position of the target is target's position at the end of the time of flight of the projectile. The future target position is equal to present target position plus the movement of the target during the time of flight, Tf. The present position of the target is its position at the instant the gun is fired.

The relative motion between own ship and the target is resolved into linear rates of motion. The rates established for the surface target are range dR and bearing RdBs. For an air target, in addition to dR and RdBs, elevation rate RdE is needed. The rates are then multiplied by Tf.

The predicted values of range, bearing, and elevation are converted into appropriate units (such as yards, mils, minutes of arc) and added to the present position of the target. Range prediction is corrected for the effects of deflection and elevation predictions. The elevation prediction is corrected for the effects of complementary error.

The rates are also used to generate a continuous present target position. The increments of generated change in target position are transmitted to the director to aid in tracking the target. This serves as a check on the rates, and provides a means for correcting them if necessary.

STEP 3—STABILIZATION

In the surface problem, stabilization takes place in the rangekeeper. Director train B'r' is measured in the deck plane. Therefore the horizontal bearing angle, Br, must be obtained indirectly. This is done by algebraically adding deck tilt correction jB'r' to B'r' to produce Br.

The deck tilt correction is calculated from values of L' and Zh (received from the stable vertical) and B'r' (received from the director).

In the air problem, stabilization is not confined to the computer. In step 1 of the problem, stabilization of the director's LOS was discussed. The director transmits two angular quantities,

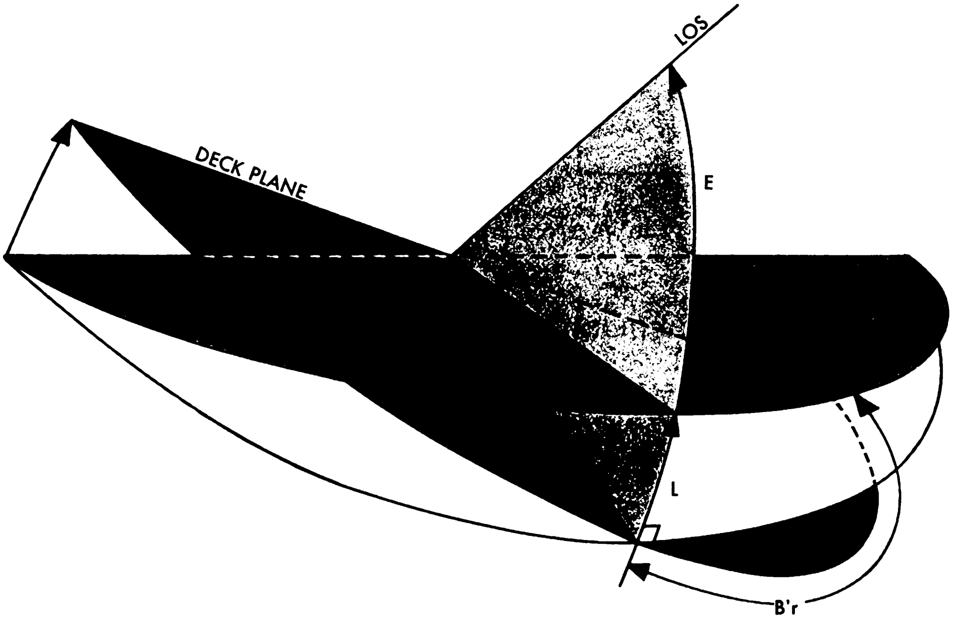


Figure 11-6.—L and Zd as measured by the stable element.

55.248

Eb and B'r, measured with respect to the deck plane. Both of these quantities must be converted to values measured with respect to the horizontal plane.

Eb, L, and E are measured in the vertical plane (fig. 11-7) which simplifies the computer's problem. In the computer, L is continuously subtracted from Eb to produce E.

Director train B'r is converted from the deck plane to relative bearing Br in the horizontal plane by deck tilt correction jB'r. jB'r is calculated in the computer in the same manner as in the rangekeeper. jB'r is algebraically added to B'r to produce Br.

Since the problem is solved with respect to the horizontal plane, and the gun moves with respect to the deck plane, the output gun orders must be converted to the deck plane. The conversion and stabilization of the LOF will be covered along with other corrections to the gun orders in step 4.

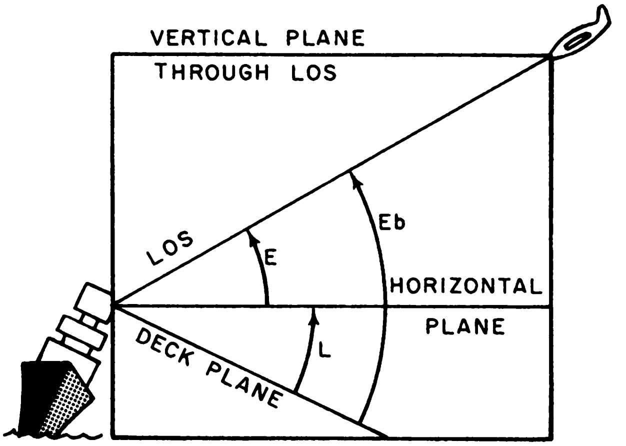


Figure 11-7.—Elevation angles in the vertical plane. 55.249

STEP 4—CALCULATE GUN ORDERS

The fourth step in the problem is the summation of the quantities which make up the gun orders, and calculation of the corrections to these gun orders. Let's discuss each gun order separately starting with gun train order B'gr.

GUN TRAIN ORDER B' gr

First we will consider gun train order in the surface problem. B'gr is the result of the addition of three angular quantities:

$$B'gr = Ds + Dz + B'r'$$

This is shown in figure 11-8.

Ds is the angle between the vertical plane through the LOS and the vertical plane through the LOF, measured in the horizontal plane. Ds is positive if the gun is trained right from the LOS. Ds is the summation of Dt, Dw, Df, and, if a spot is applied, in deflection Dj.

Dz is the trunnion tilt correction to compensate gun train order for the tilting of the gun trunnions in crosslevel. Dz also refers the Ds input to B'gr to the deck plane.

Ds and Dz are added in the rangekeeper to give total deck deflection Dd'. Therefore you can write

$$Dd' = Ds + Dz$$

and it follows that

$$B' gr = B'r' + Dd'$$

Gun Train Order in the Air Problem

In a similar manner, B'gr in the air problem is the sum of director train B'r and total deck deflection Dd:

$$B'gr = B'r + Dd$$

For convenience, Dd is divided into two parts: (1) Dz, the train correction for trunnion tilt, and (2) jDd (partial deck deflection), the projection of Ds onto the deck plane. Dd is the sum of Dz and jDd.

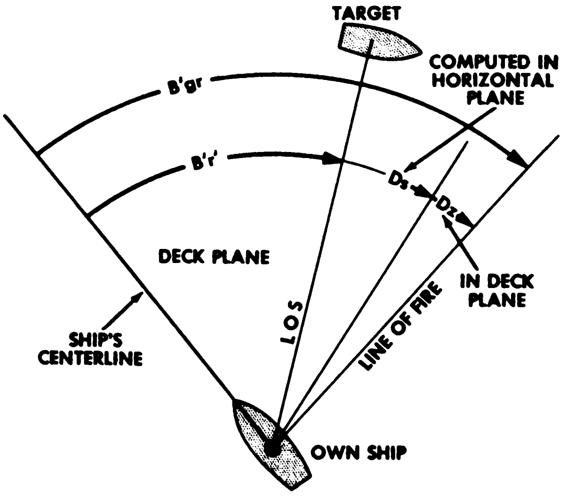


Figure 11-8.—Gun train order. 55.250

The true equation for Dz and jDd is complex, and cannot be solved without the use of many mechanisms. Because of this, modified equations are used. Consequently, the mathematical formulas are of little importance to you. However, you should recognize and understand the quantities Dz and jDd.

Trunnion Tilt

A basic explanation of the effects of trunnion tilt is given in the three drawings of figure 11-9. In figure 11-9A the deck is level and gun orders have been computed to score a hit. Now the ship rolls. Since the gun can only elevate perpendicularly to the deck, the bore axis of the gun swings off to the right, as is shown in figure 11-9B. The gun, therefore, must be trained uphill to get back on target. In so doing, naturally you raise the gun too high (fig. 11-9C) and have to lower it to compensate.

The angles through which the gun is trained and depressed to bring the axis of the gun back into coincidence with the LOF are called Dz (the train correction due to crosslevel) and Vz (the elevation correction due to crosslevel). See figure 11-9C.

This is the same basic trunnion tilt problem we covered in the surface problem. The trunnion tilt corrections change the gun orders to keep the gun on the LOF regardless of how the deck tilts.

The quantities involved in the calculation of trunnion tilt are gun elevation and crosslevel. In figure 11-10 it has been assumed that Vs and Ds are zero. In this illustration you can see that, for the same value of crosslevel, Dz and Vz increase with gun elevation. It is apparent that as Zd increases, Dz and Vz will also increase.

Vz, elevation trunnion tilt correction, is a part of gun elevation order and will be covered later.

jDd Partial Deck Deflection

The major difference between the geometry of the surface and air problems is the high elevations which are possible in the air problem. Because of these high elevations, the air problem is solved in the slant plane. Therefore Ds, although calculated in a plane parallel to the horizontal, is measured in an elevated plane. Ds is the angle between the vertical plane that contains the LOS and the vertical plane that contains the LOF, and is measured in the slant plane. This is shown in figure 11-11. In the figure, L and Zd are zero.

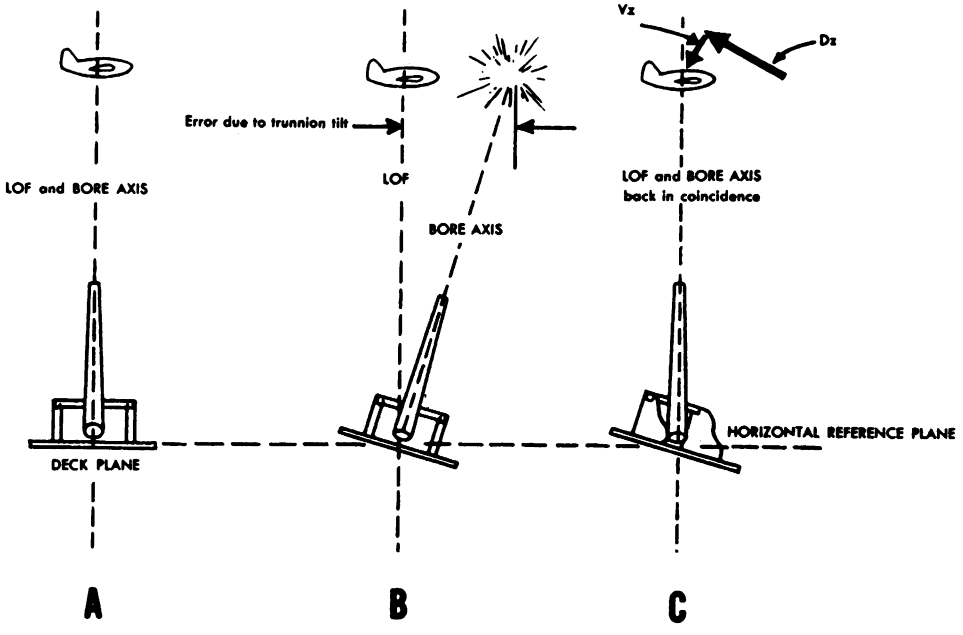

Vz
Dz
Error due to trunnion tilt
LOF and BORE AXIS
LOF
BORE AXIS
LOF and BORE AXIS back in coincidence
HORIZONTAL REFERENCE PLANE
DECK PLANE
A
B
C

Figure 11-9.—The effects of trunnion tilt.

55.251

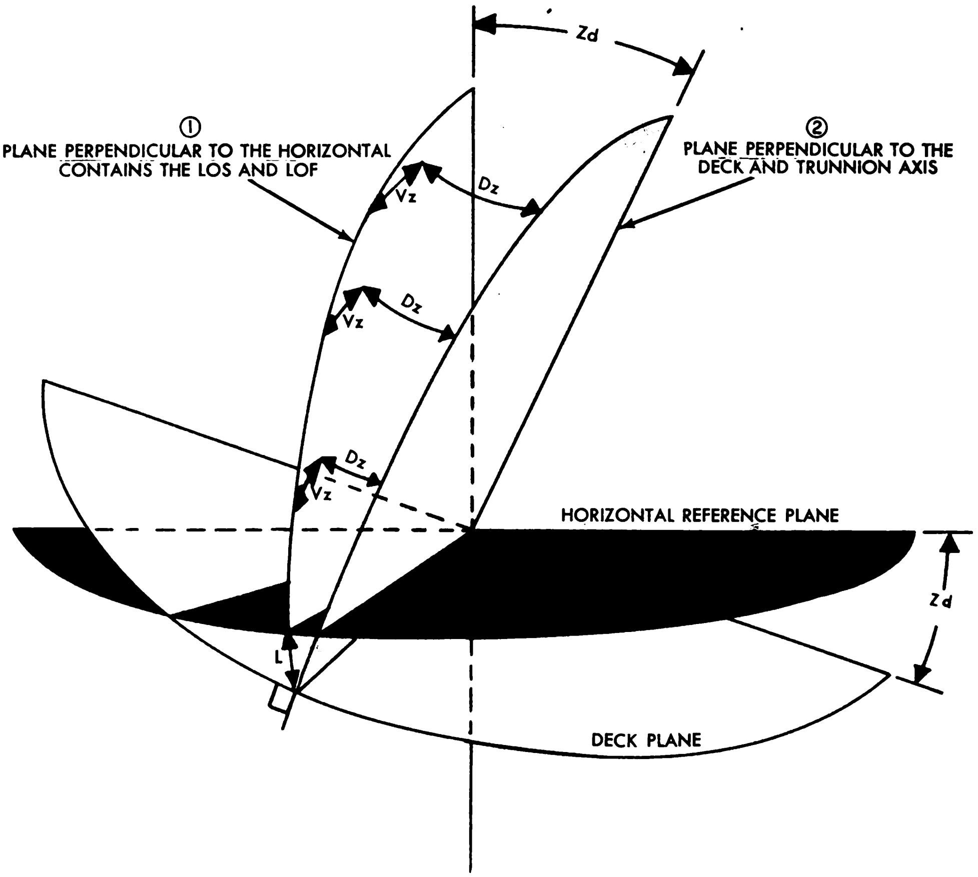

Zd
①
PLANE PERPENDICULAR TO THE HORIZONTAL
CONTAINS THE LOS AND LOF
②
PLANE PERPENDICULAR TO THE
DECK AND TRUNNION AXIS
Vz
Dz
Vz
Dz
Dz
Vz
HORIZONTAL REFERENCE PLANE
Zd
L
DECK PLANE

Figure 11-10.—Trunnion tilt corrections increase with elevation.

55.252

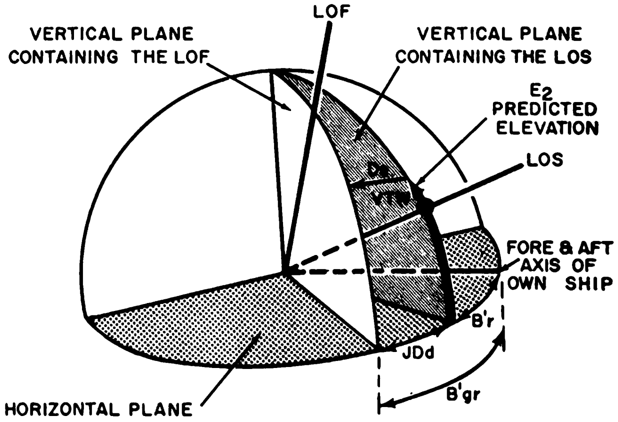
Here is the difficulty: the gun can train only in the deck plane; therefore Ds must be transposed from the slant plane to the deck plane.

jDd is the projection of Ds onto the deck plane. When L and Zd are present, the deck is tilted out of the horizontal plane, in which case the offset of jDd is made on an inclined plane. It is apparent that jDd must be corrected for the effects of L and Zd.

Here again an approximate formula was derived which will give satisfactory values of jDd.

jDd varies directly with predicted target elevation; that is (for a given Ds), as predicted target elevation increases, jDd will increase proportionally. This can be visualized from figure 11-11. With a little reasoning you can see that as L and Zd vary, jDd will also vary. And, naturally, as Ds in the slant plane increases, jDd in the deck plane will also increase.

The stabilization factors in jDd and Dz are confusing, but let's see if we can separate them. Dz corrects B'gr for trunnion tilt but is related to the LOS. The offset of Ds has not been applied. Therefore when we apply Ds, a correction for the inclination of the deck plane must be included as an integral part of the LOF offset.



55.253

Figure 11-11.—jDd partial deck deflection.

Horizontal Parallax

Gun fire control systems compute values of gun orders measured with respect to a reference point. Therefore, the orders to a gun not located at the reference point must be modified. The gun's line of fire is positioned to converge with the line of fire computed for the reference point, so that they coincide at the aiming point. The amount and direction of modification of the gun's LOF is determined by the gun's location with respect to the reference point.

Horizontal parallax is illustrated in figure 11-12. You are acquainted with this type of parallax from your previous studies. You know that it is a correction to gun train. Here we will cover the factors which effect horizontal parallax. These factors, which are similar in the air and surface problem, are: baselength, bearing, and range.

To start, we will use a simple system consisting of one gun and one director, with the reference point located in the director.

You'll recall that the distance of the gun from the reference point is called baselength. Horizontal baselength is measured in the deck plane, parallel to the ship's centerline. This distance is always measured in the deck plane even though "horizontal" is part of its name.

The effect of horizontal parallax is greatest when the target is directly abeam. Assume that sight deflection is zero, and that the deck and trunnion tilt corrections are zero. Then, since B'gr = B'r' + Ds + Dz, gun train order would equal B'r' because B'gr = B'r' + O + O.

But if the gun were trained through angle B'gr, the projectile would not hit the target, as shown by figure 11-12. Therefore, to score a hit the gun must be trained around farther, through the horizontal parallax angle, Ph.

Parallax angle may be thought of in two ways—(1) the angle at the gun between the gun LOS and a line running through the gun parallel to the director LOS, or (2) the angle at the target between the gun and director LOS. It is clear from figure 11-12 that these two angles are equal.

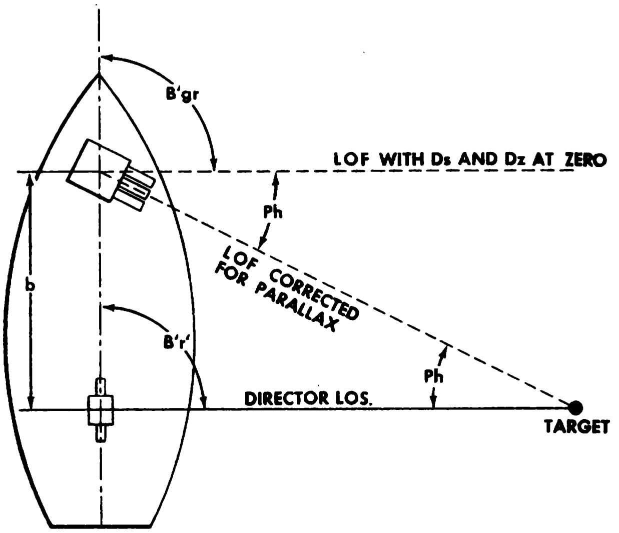


Figure 11-12.—Horizontal parallax with target abeam. 55.254

It should also be clear from the illustration that angle Ph depends on the baselength. (Ph is usually a very small angle; for that reason it is sufficiently accurate to say that it is directly proportional to baselength.) Since Ph is a correction to gun train, only that part of the baselength that is across the LOF should enter into Ph. When the LOF is directly on either beam, the entire baselength is ACROSS the LOF. In figure 11-13 the LOF is directly ahead. It is obvious that the entire baselength is IN the LOF and will affect only the range. Therefore, when the LOF is directly ahead or astern, Ph is zero.

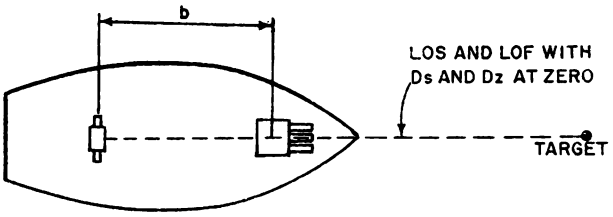


Figure 11-13.—Horizontal parallax is zero when the target is directly ahead. 55.255

Figure 11-14 shows a target at an angle between zero and 90 degrees. Line b', drawn perpendicular to the LOF, is the amount of the baselength across the LOF. It has been found that the portion of the baselength across the LOF varies directly as the sine function of B'gr. It follows then that Ph varies directly with the baselength and as the sine of B' gr.

It can be seen from figure 11-15 that as range increases, Ph decreases. Since we are dealing with the LOF advance range, R2 is used. Therefore Ph is indirectly proportional to R2. Normally in fire control systems the reciprocal of R2 is used in the calculation of Ph.

The Ph problem is solved in the deck plane. Range to an elevated target is measured in the

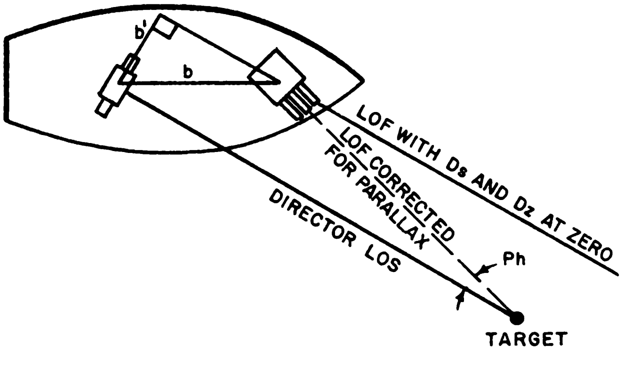


Figure 11-14.—Baselength b' across the LOF.

slant plane. Consequently, in the air problem, slant range must be converted to deck range. This is accomplished by the use of the cosine function of the angle of predicted elevation above the deck plane (E2 + L).

Now let's look at the problem when the GFCS has more than one gun mount. We know that Ph is directly proportional to baselength. Obviously we must compute a separate Ph for each baselength. In some surface batteries this is exactly how it is done. However, each station must have its own individual Ph computer. The inputs to the computer are B'gr and parallax range ($\frac{1}{R2}$). The baselength of each station is a constant in the computers.

An alternate method is to compute Ph for a standard UNIT baselength. Unit baselength is usually 100 yards. This method requires just one Ph computer whose output is called unit parallax. Each station receives unit parallax. Since Ph varies directly with baselength, each station uses an amount of the unit parallax proportional to its distance from the reference point. The individual baselength correction is accomplished by parallax change gears, with different gear ratios. For example, if the baselength is 50 yards, a 2:1 stepdown gear ratio would be used to obtain the correct parallax.

Director Parallax

Now let's look at a system containing more than one director. If we have intercontrol between directors and between batteries, we must have a common reference point. (Fig. 11-16.) Here the reference point is located at the forward director. Notice that the train angle for the after director is smaller than that of the forward director. You can see that we have the same parallax problem between the two directors as we have between a director and gun mount.

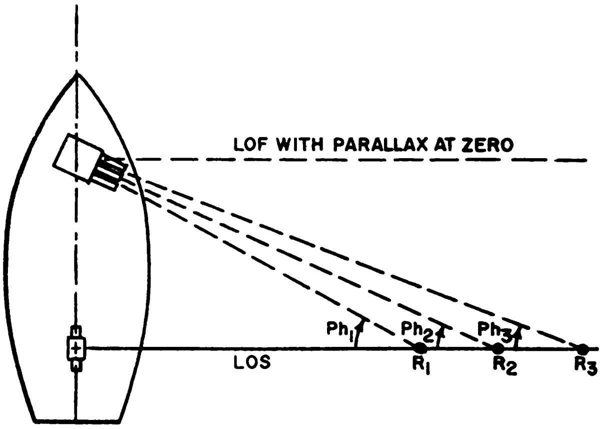


Figure 11-15.—Horizontal parallax varies with range. 55.257

To remedy this difficulty a parallax correction, Ph, is added to the after director's train angle. Thus the after director does not transmit actual director train; instead, it transmits the value which director train would have if the forward director were tracking the target.

In some installations, all the directors have a parallax correction added to director train. Then each director transmits the value which director train would have if the director were located at some common reference point, as shown in figure 11-17. In other words, each director measures director train as if it were located at a common point.

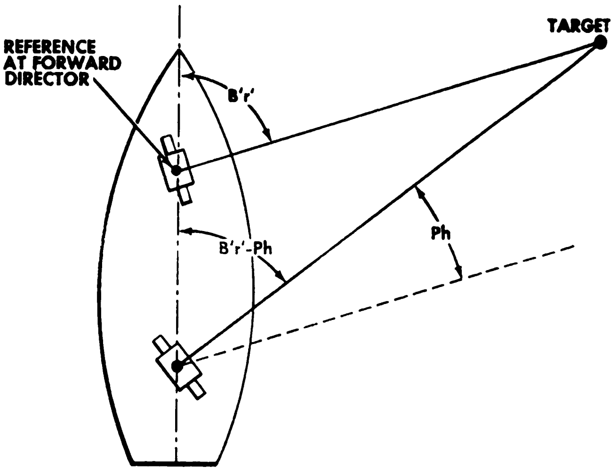


Figure 11-16.—Parallax between two directors.

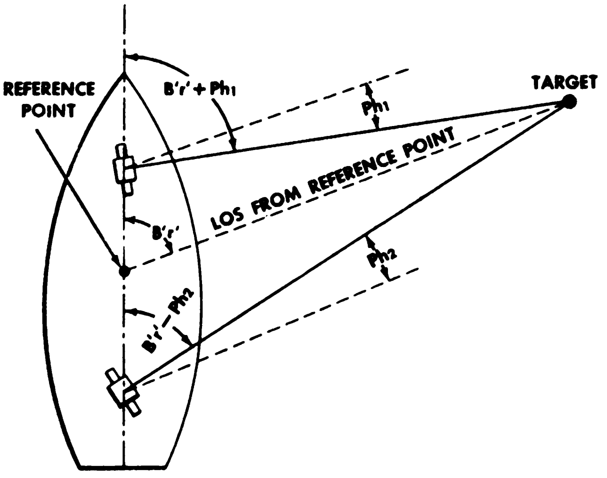
It is evident that when all directors and guns are corrected for horizontal parallax with respect to some common reference point, any one director can control any gun or guns.

When we covered the parallax problem for the guns, the LOF was used as the reference line; but when we considered the problem for the directors, the LOS was used. Theoretically, the parallax between directors and the reference point should be based on present relative bearing, and the parallax between guns and the reference point should be based on B'gr.

In a system in which each station has a parallax computer, this can be done. However, in a system which calculates unit parallax, either B'r or B'gr is the angular input to the parallax computer. In a single director installation the director is the reference point; the director requires no parallax correction, and B'gr is used to compute Ph. In multiple director installations, the directors require parallax correction, and B'r is used to compute Ph.

In the latter case, Ph to the gun mounts contains an error. However, at the average firing range this error is so small that it can be disregarded.

All the stations in the system are trained on a single point. The thought that each station would have a different train reading might have crossed your mind. To eliminate confusion, Ph is introduced into the controls of the train drive by the response line. By introducing Ph in this manner each station will have the same train reading, although its actual bearing is different.



55.259

Figure 11-17.—Director horizontal parallax corrected to a common reference point.

Ph is considered positive when it causes right train, and negative for left train. The sign of Ph is determined by bearing and the direction of unit displacement from the reference point. Naturally, the sign of Ph for an element forward of the reference point would be opposite to that for an element aft of the reference point.

GUN ELEVATION ORDER E'g

Gun elevation order E'g is the ordered angle between the gun bore axis (LOF) and the deck plane, measured perpendicular to the deck plane. Let's consider first the simple case of a surface target when the deck plane is level. Since a surface target is considered to be in the horizontal plane, E'g = Vs (fig. 11-18). You'll recall that in the surface problem Vs is obtained from a cam positioned by R2.

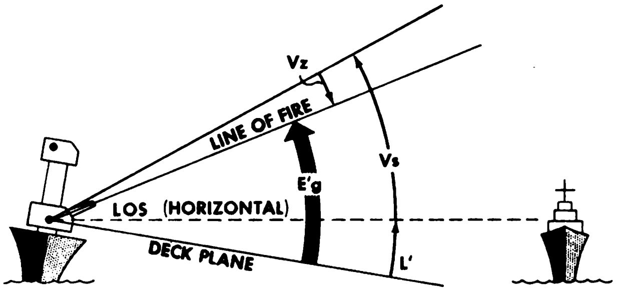


Figure 11-18.—Gun elevation order. 55.260

Vs contains ballistic corrections that are computed in relation to the horizontal plane. Therefore, if the deck is level and R2 is calculated correctly, Vs, and hence E'g, will also be correct. But since E'g is measured from the deck plane, when the deck tilts out of the horizontal plane E'g must be corrected.

We know that trunnion tilt affects E'g. The trunnion tilt correction for elevation (Vz) can be seen by referring back to figure 11-10. Notice in the figure that Vz is a negative (down) correction. If you think about it, you can see that with the deck tilted, Dz causes the gun to train in an inclined plane and always uphill. Thus Vz is always negative. Vz is algebraically added to Vs in the rangekeeper. In the formula for E'g you will see both forms: Vs - Vz and Vs + Vz. But remember, Vz is negative and when the + sign is used, algebraic addition is indicated.

Since the deck is tilted there is one more angle to be added to Vs + Vz to obtain E'g. This is the angle L', as shown in figure 11-18. L' is the compensation for the deck tilt in the plane containing the LOS. L' is normally transmitted from the stable vertical to the rangekeeper. As shown in the figure, gun elevation order is equal to

$$E'g = Vs + Vz + L'$$

Director Elevation and Vertical Parallax

When the surface system is in full automatic operation, it is not necessary to use director elevation in the computation of the gun orders. Gun elevation order then is computed entirely by the rangekeeper and stable vertical.

In the event of stable vertical failure, some other method of measuring L' must be available before E'g can be computed. This is accomplished by the director as it measures E'b. E'b for surface fire is essentially equal to L'; in fact, it would be equal to L' if the gun and director were located the same height from the deck. But this is not the case because the director is invariably located above the gun.

Consequently, vertical parallax Pv must be considered. Vertical parallax is caused by vertical distance h between the director and gun, as shown in figure 11-19. The value of Pv is roughly equal to vertical distance h multiplied by parallax range $\frac{1}{R}$. This multiplication of inverse range by the constant h is performed in a gear ratio at the director.

A handcrank and dial drives inverse range through a set of change gears into a differential in the line from the pointer's handwheels to the level synchro transmitters, as shown in figure 11-20. The dial is graduated so that it reads present range, but actually, INVERSE RANGE is the quantity that is set in. Then the elevation of the gun LOS, or level, becomes the quantity that is transmitted to the rangekeeper in plot.

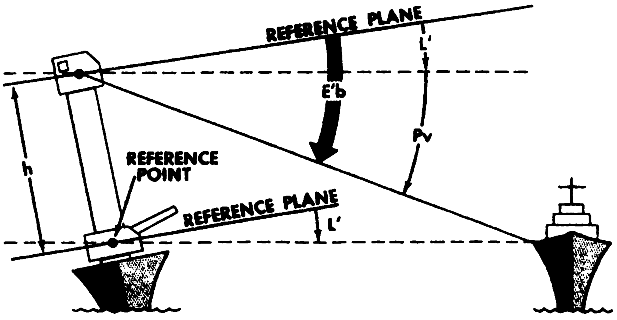


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Figure 11-19.—Vertical parallax is taken into account when measuring L' at the director.

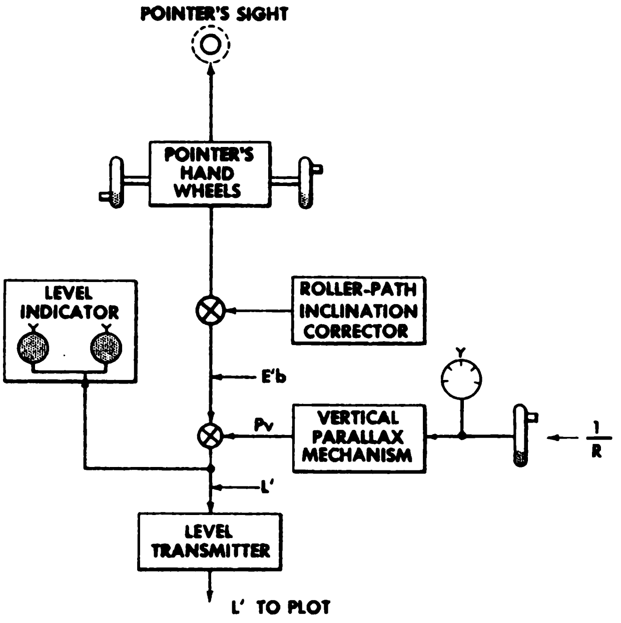

Figure 11-20.—Inverse range is cranked in at the director. 55.262

E'g in the Air Problem

In the air problem the formula for gun elevation order is

$$E'g = Eb + Vs + Vz$$

It appears that the only change in the formula between the air problem and the surface problem is that Eb (director elevation) is substituted for L'. It also stands to reason that the quantities which make up Vs will be different in the air problem.

Let's see how Vs is made up in the air problem. The formula for Vs is

$$Vs = V + (Vf + Pe) + Vfm$$

The quantity V is equal to

$$V = Vtw - Vx + Vj$$

Vtw, you will recall, is the compensation for the relative motion of own ship and target and the effect of apparent wind in elevation. Vx is the complementary error correction which compensates for the change in elevation due to deflection prediction. Vj is the elevation spot.

It is necessary to calculate V in order to obtain predicted target elevation E2. E2 is equal to E + V and is used in the calculation of Vf + Pe.

Vf (superelevation) you'll recall, varies as a function of E2 and R2 and is computed by a ballistic cam.

Pe (elevation parallax) compensates for the height of the director above the gun trunnions (fig 11-21). The distance between the gun trunnion heights is small. Therefore the vertical distance between the director and guns, called bv, is assumed to be a constant—usually 10 yards. Thus Pe can be included directly in E'g.

As you can see from figure 11-21, Pe depends upon bv, advance range and predicted elevation. (This is the same type of problem as Ph, but rotated 90 degrees.) Since bv is a constant, Pe depends upon R2 and E2, and can be computed by a ballistic cam. In the Computer Mk 1A, Pe is calculated with Vf in one cam. The output of the cam is Vf + Pe.

Since the Vf + Pe cam is cut for standard initial velocity I.V., a change in I.V. will result in an error in Vf + Pe. The quantity (vfm) is a correction to Vf + Pe for any change in I.V. The quantity (Vf + Pe) + vfm is added to V to obtain Vs.

The quantity (Vz) in the formula for E'g is the elevation trunnion tilt correction. It is the same quantity as in the surface formula for E'g.

Thus, Eb + Vs + Vz is the computed gun elevation order transmitted to the gun mounts. However on some carrier installations another parallax correction to gun elevation is necessary. This parallax (Pv) is due to a horizontal base as shown in figure 11-22.

Although the symbol Pv is the same as that for elevation parallax in the surface problem, don't confuse the two. Keep in mind which problem you are referring to when speaking of Pv.

In figure 11-23, you can see that the vertical parallax effect of a horizontal base is distance A divided by R2. And, neglecting Pe, AD equals Dh cosine B'gr sin (E2 + L). The baselength (bh) is the same as Ph, a constant of 100 yards.

Pv is transmitted from the computer to the gun mount's elevation power drive. There it is handled in the same manner as Ph is in the train drive.

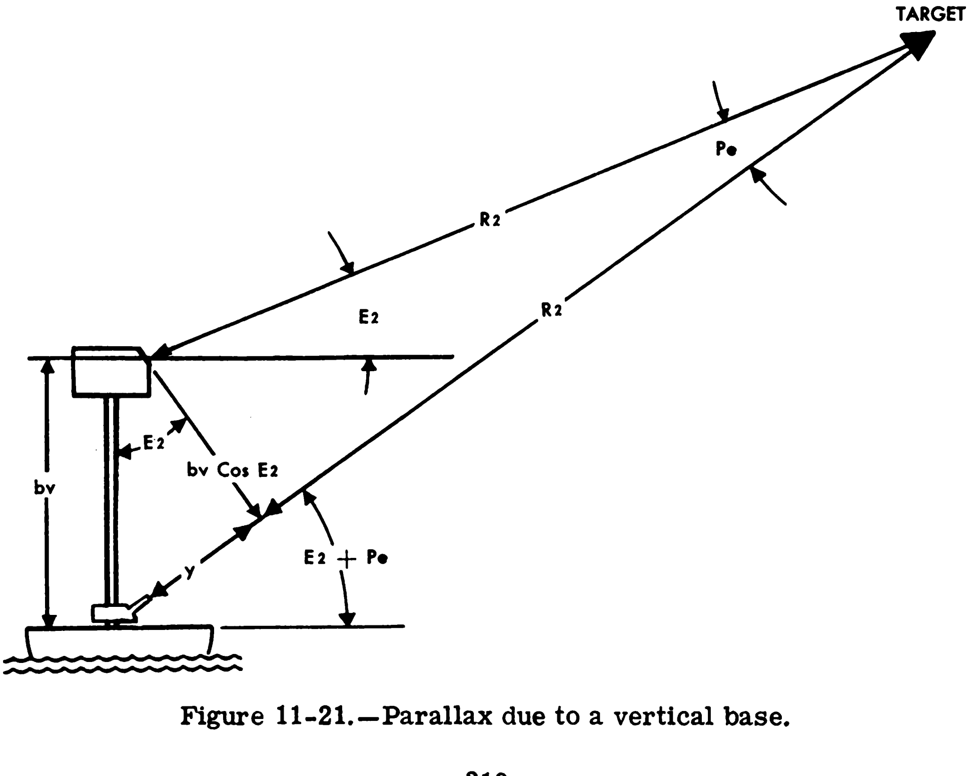

Figure 11-21.—Parallax due to a vertical base.

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Reference Plane

The elevation of all elements of a battery is measured from a standard reference plane. The reference plane is an arbitrarily selected plane, approximately parallel to the deck. It may be the actual roller path of any one element, or an imaginary plane. Where an imaginary plane is used, it is normally a "mean plane" or "resultant plane" of all the elements' roller paths.

The reference plane is necessary because no two elements in a battery have parallel roller paths. One element may tilt astern, another to port or to starboard. These roller paths deviate from each other by only a few minutes of tilt. But a few minutes may mean a miss at a range of several thousand yards, so a reference plane common to all battery elements is chosen and then all elements are corrected to this reference.

The battery elements are corrected to the reference plane by a roller path compensator. Each element in the battery (other than a reference element) has a roller path compensator or is shimmed to the reference plane.

FUZE SETTING ORDER

The fuze of a projectile must be set so that the projectile will burst at the predicted target position. Fuze setting order F is the computed fuze time in seconds.

The projectile's fuze is set several seconds before the instant of firing. The time between the setting of the fuze and firing is called dead time

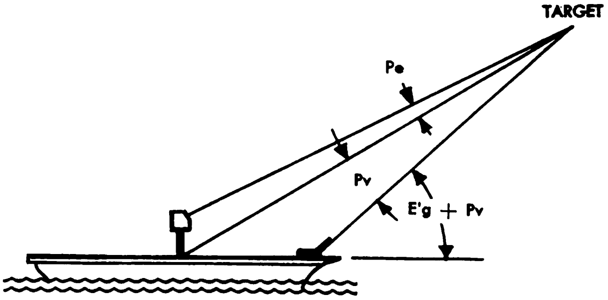

Figure 11-22.—Elevation parallax due to a horizontal base.

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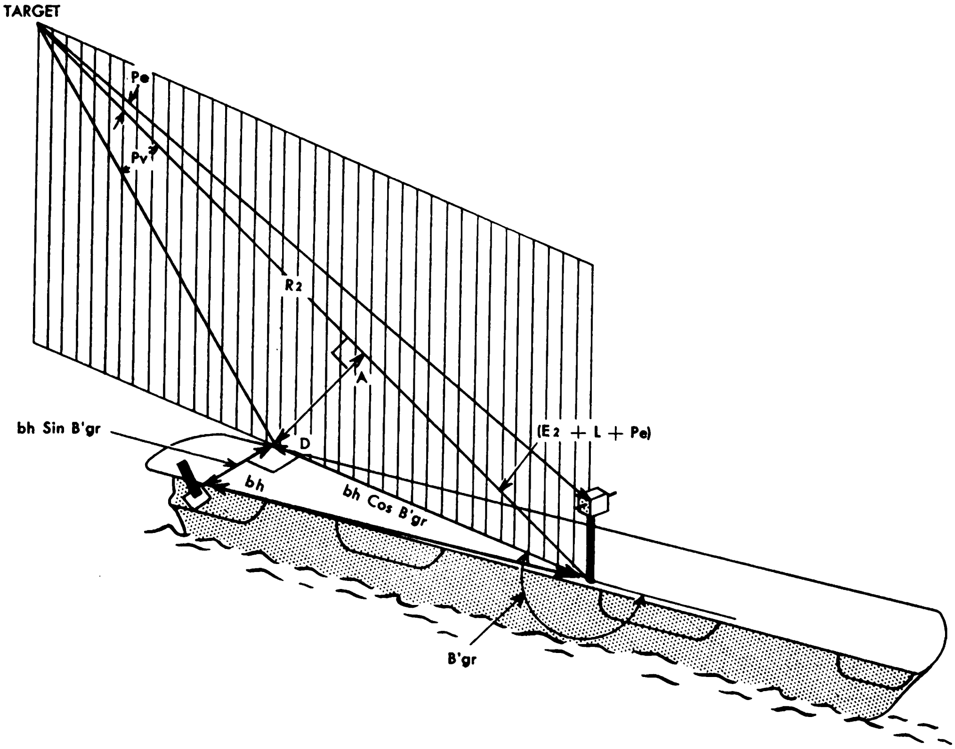

Figure 11-23.—Elevation parallax Pv.

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Tg. If it were not for Tg we could use Tf for fuze time. Target's movement during Tg must be predicted. This can be done by multiplying range rate by Tg. The product is added to R2 to obtain fuze range R3. R3 and E2 are inputs to a ballsitic cam whose output is F.

STEP 5—TRANSMIT DATA TO GUNS

Most information that flows into the gun orders is transmitted and received electrically by synchro transmitters and receivers.

Figure 11-24 is a simplified diagram of a main battery fire control system showing how quantities that help make up the gun orders are received by synchros from the director and stable vertical, and how the rangekeeper outputs and the gun train and elevation orders are transmitted by synchros. A thorough understanding of this setup will help you in troubleshooting in both the main battery and dual purpose fire control systems because they are laid in essentially the same way.

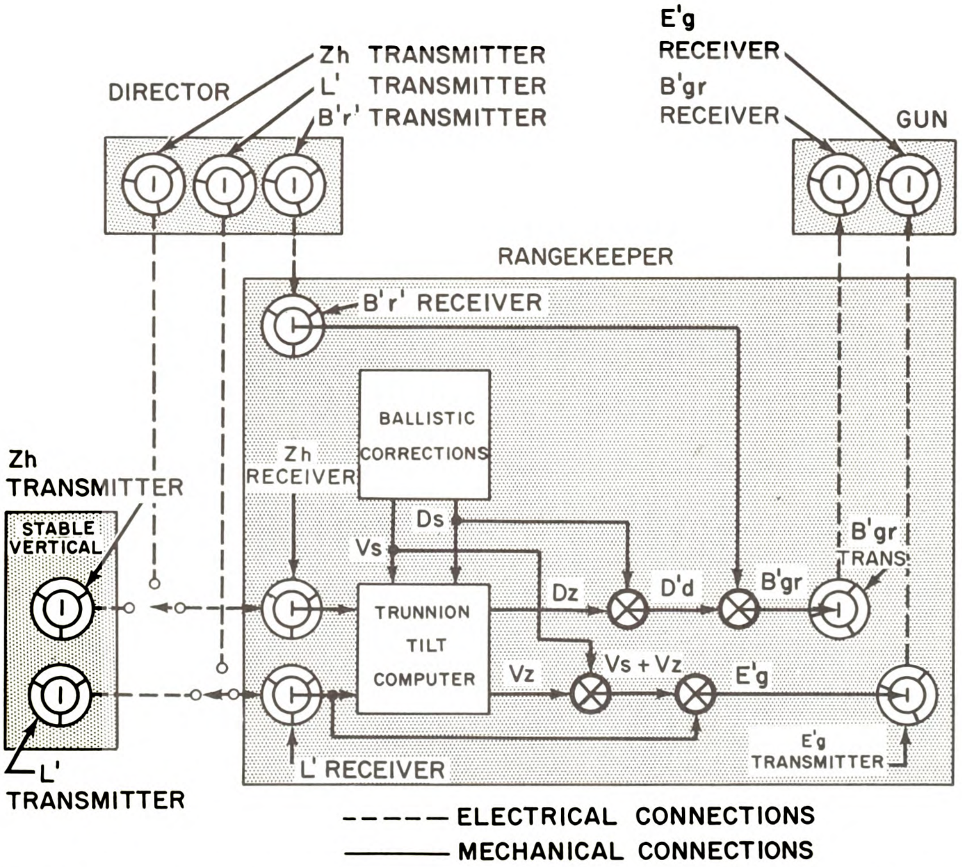

Figure 11-24.—Quantities that make up the gun elevation and train orders are transmitted and received by the synchros.

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CHAPTER 12

SUBMARINE FIRE CONTROL

One of the two probable seagoing assignments for an FT(G) is duty aboard a submarine. If you are an FT(M), you may skip this chapter. But it is recommended that the FT, regardless of his specialty, who is really interested in broadening his knowledge of the fire control fields, should read and study this chapter. You will see many similarities between the underwater, gun, and missile fire control problems. The terminology may be slightly different, but the underlying fire control principle is the same in all the problem variations.

Fire control, as you well know by now, is the science of aiming a missile (projectile, guided missile, torpedo, or other destructive device) so that it will hit the target. Before we go into the underwater problem, let's take a look at the ship that carries the torpedoes.

Figure 12-1 shows what an up-to-date submarine looks like when it is on the surface. But there is more to a sub than you see in the picture. Even on the surface, a sub sits low in the water; it is both wider and deeper than you'd guess from looking at it. And of course when it is submerged you see only the slender tip of its periscope, or maybe nothing at all.

It's this invisibility that gives the submarine its principal tactical value—its ability to approach a much larger ship, deliver a lethal punch, and run—all without being seen. And there you have the key to its strategic use. The submarine can carry the fight to the enemy, even in waters where the enemy controls the surface and the air above it. For example, we made good use of submarines in World War II. After Pearl Harbor, the Japanese had almost complete control of the western Pacific—at least on the surface. But we sent our subs under the surface. What happened? American submarines sank two-thirds of the Japanese Merchant Fleet, and one-third of the Imperial Japanese Navy.

World War II in the Atlantic was just the other way around. There, the American and British had control of the surface. But in 1942 the German submarines were sinking our ships in the Atlantic a lot faster than we could build them. As in the First World War, the Germans and their submarines came close to winning before we could even get started.

The part that subs could play in case of another war is anybody's guess. It seems likely that, as in the past, we'll depend heavily on convoys, and that the enemy will use his submarines to attack them. It is an educated guess that we'll use our submarines to hunt and kill those of the enemy.

THE BASIC SUBMARINE FIRE CONTROL PROBLEM

The problem of aiming a torpedo so that it will strike a moving target is similar to the problem encountered in gun and guided missile fire control. The target moves across the line of sight, and a torpedo aimed directly at the target will miss because the target moves as the torpedo travels from the tube toward the intended victim. Thus it is necessary to fire ahead of the target to hit it.

The gun projectile and the torpedo have the same objective so it is interesting to compare the factors that affect the paths of these missiles. The ship on which the guns are mounted is moving forward, and it may be pitching and rolling as well. The target itself is moving. If it's an aircraft, it may be moving hundreds of feet each second. The path of the projectile, from gun to target, depends on many things. Here are some of them: the kind, weight, and temperature of the propellant charge; the force and direction of the wind, both at sea level and high in the air; the pressure of the atmosphere; and the "drift" of the projectile due to its rotation.

To all of these factors you add the motion of your own ship, and the range, course, and speed of the target. The gun fire control system

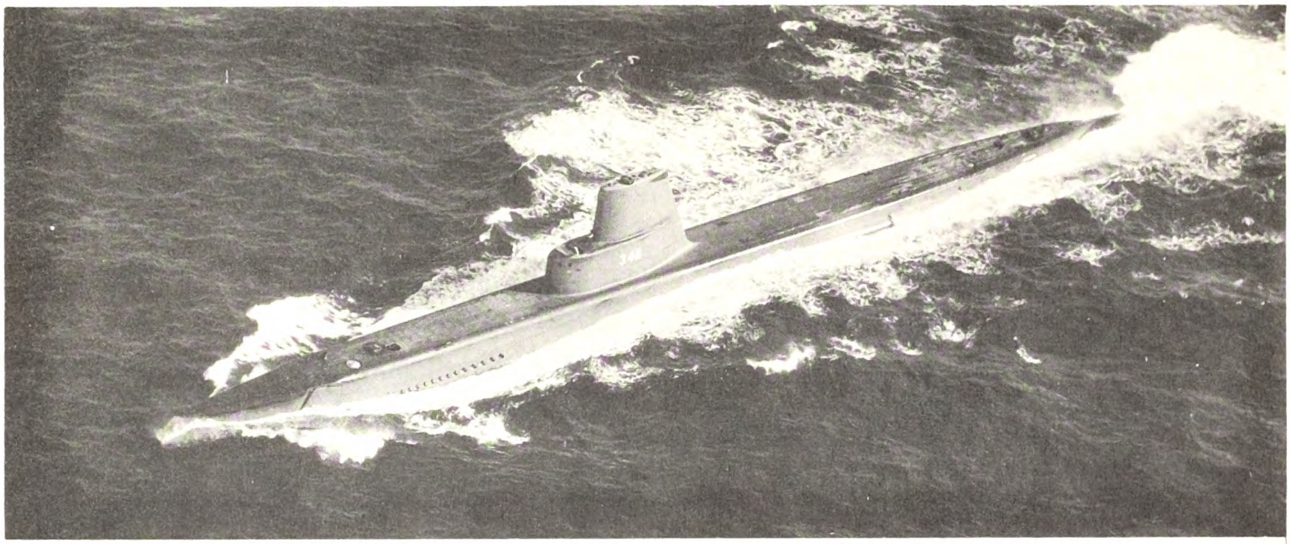


Figure 12-1.—Submarine underway on the surface. 55.267

absorbs all that information, and comes up with an answer. What does the answer consist of?

As you know, it consists of two parts. If the projectile is to fall on the target, rather than to the right or left of it, you must have the proper gun train angle. If the projectile is to fall on the target, rather than beyond it or in front of it, you must have the proper elevation angle. So, for a gun, the solution to the fire control problem, at any given instant, is two angles.

In some ways the submarine torpedo fire control problem is even harder. First of all, you can't train the tubes the way you do a gun. The underwater tubes are immovably fixed to the hull. Second, a torpedo moves a lot slower than a projectile. During the torpedo run, the target may move a considerable distance. And that means you must lead it by a large angle. Third, a surface ship has rangefinders and/or radar to measure the target's range. On the other hand, the submarine's range measuring capability is limited. The range measuring equipment on board a submarine consists of a stadimeter in the periscope, and sonar. However, if either of these instruments is used for ranging, the submarine increases the possibility of its detection.

In other ways, the torpedo problem is simpler. You don't have to worry about the wind, or the pressure of the atmosphere. You don't have to aim above the target in order to hit it, because the torpedo doesn't fall during its run; its control system keeps overcoming the force of gravity. Also torpedoes are usually set to run at a certain depth. So there's no elevation angle to worry about.

The basic solution to the torpedo fire control problem has only one primary part. It is deflection angle, although it is not always called that.

Figure 12-2 shows the basic torpedo triangle for straight fire. Straight fire means that no maneuvers are required of the torpedo during its run from the launching tube to the target. To solve the straight fire triangle, the following information must be known.

1. R (range), the distance from the firing submarine to the target at the time of launch.
2. Br (relative target bearing), the angle between the firing submarine's bow and a line drawn from the submarine to the target (LOS) measured in a clockwise direction from the submarine's bow at the time of torpedo launch.
3. St (the speed of the target).
4. Sz (the speed of the torpedo).
5. A (target angle), the angle between the bow of the target and a line from the firing submarine to the target measured in a clockwise direction from the bow of the target at the time of torpedo launch.

Fundamentally, the above information is the same as the information you need to solve the gun and missile fire control triangles.

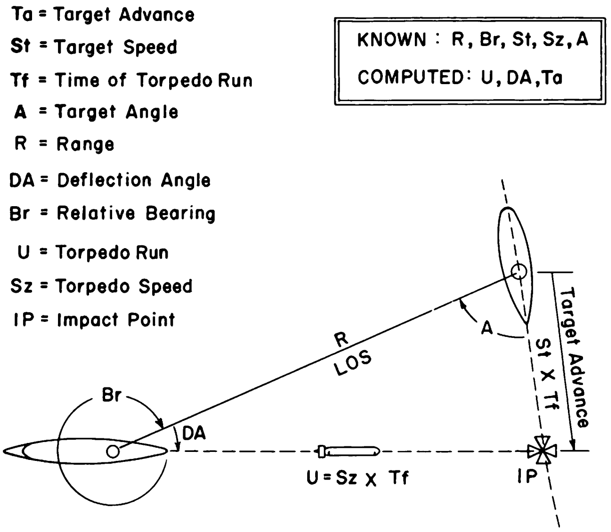


Figure 12-2.—Basic underwater fire control triangle (straight fire). 55.268

Using the known information about the target, four values are computed by the submarine fire control system. These are:

1. Tf, the time it takes the torpedo to travel from the tube to the point of impact. This value is not used by the torpedo but is needed by the fire control system to compute torpedo run and deflection angle.

2. StTf (target advance), the distance the target travels while the torpedo is traveling from the tube to the point of impact. This value is not used by the torpedo but is needed to compute the torpedo run and deflection angle.

3. U (torpedo run), the distance the torpedo travels from the tube to the impact point.

4. DA (deflection angle), the angle between a line from the firing submarine to the target (LOS) at the time of launch and a line from the firing submarine to the point of impact (line of fire). The deflection angle is the lead or prediction angle.

HOW TO FIND TARGET SPEED AND TARGET ADVANCE

If a car travels 50 miles per hour for 3 hours, you know that it has traveled 150 miles. You get the distance it travels by mulitplying the speed of the car by the time it was on the road. The same rule applies to a torpedo. By multiplying the torpedo speed, Sz, by the time it travels, Tf, you get U—the distance the torpedo travels. This is called torpedo run.

The same kind of reasoning applies to target advance. This value can be found by mutiplying the target speed by the time it takes the target to travel from the point it occupied at torpedo launch to the impact point. This time is the same as the time the torpedo takes to get to the impact point. If the torpedo is to collide with the target. The target advance is equal to St times Tf.

EFFECT OF CHANGE IN TARGET ADVANCE

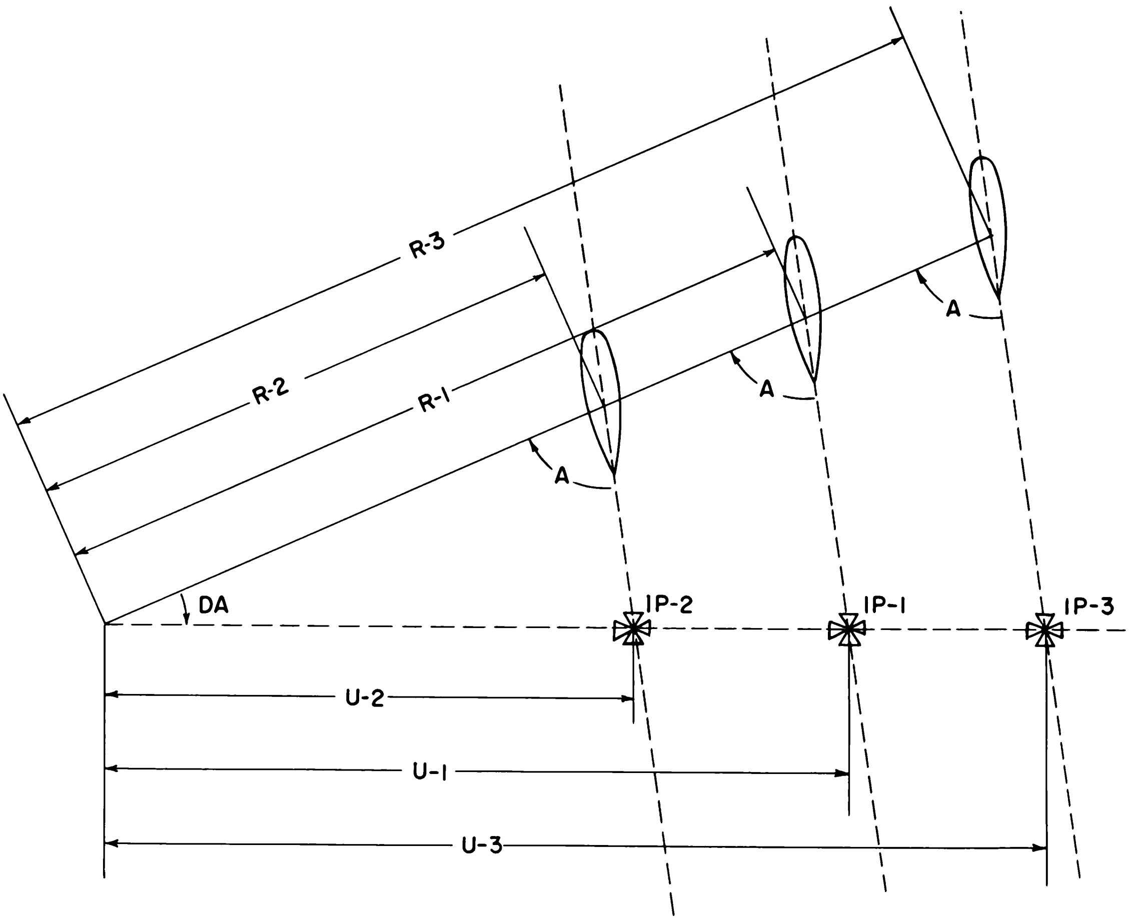
The deflection angle will change if the value of target advance changes. You can visualize the effect if you look at figure 12-2. If the target advance increases, the impact point is moved further along the target track. For the torpedo to cross the target track at the new impact point it is necessary to increase the deflection angle.

EFFECT OF CHANGE IN RANGE

If the target range is increased, the deflection angle will remain the same, but the torpedo run will increase if it is constant. The effect of an increase in range on the basic triangle is indicated in figure 12-3. Target advance, as you just learned, is equal to St · Tf. Also, torpedo run is equal to Sz· Tf. The ratio of target advance, (which is one side of the triangle) to torpedo run, (which is another side) is then St · Tf/Sz · Tf = St/Sz. Since for any particular fire control problem Sf and St are constants, the ratio St/Sz is a constant, and the ratio of target advance to torpedo run is a constant. As the range increases, the target advance and the torpedo run increase in proportion. This leaves the deflection angle always the same if range increases but A remains unchanged.

EFFECT OF CHANGE IN TARGET SPEED

If the target speed is changed, both U and DA may change. The effect of changes in target speed are shown in figure 12-4. As St increases, the impact point moves forward along the target track. This means that DA becomes larger. This is true for any values of R, Br, or A. In the situation shown in figure 12-4, U also has increased. This is true if, at the time of impact, the torpedo is catching up with the target. That is, the angle between the bow of the target and the torpedo track, measured from the bow of the target in a clockwise direction, is between 90°



NOTE: *Lead triangle shape results from ratio of* $\frac{St}{Sz}$ *and is independent of range.*

Figure 12-3.—The effect of range. 55.269

and 270°. If the target is coming toward us, then an increase is speed will lengthen target advance and bring the impact point closer to the firing submarine. In this case, U will be shorter. These situations are reversed if target speed is reduced.

EFFECT OF CHANGE IN TARGET ANGLE

Target angle (A) is an indirect measurement of target course. Thus a change in A will cause a change in the impact point and effect both U and DA. This is shown in figure 12-5 A and B. In figure 12-5A the target is in the center of a circle which is divided into quadrants. Target speed is constant in the illustration and a line is drawn to the firing submarine. The effect of target angle changes on U and DA is shown vectorially by the vectors marked U and DA.

In figure 12-5B the impact point (IP) is shown for three target angles. In these three examples the target is heading toward the firing submarine. Notice how U and DA vary with A.

EFFECT OF CHANGE IN TORPEDO SPEED

The speed of the torpedo affects both U and DA. Refer to figure 12-6 to see the effect. If the torpedo speed increases, Tf decreases. This means that the target advance decreases and the impact point moves back along the target track. Notice too that the deflection angle decreases.

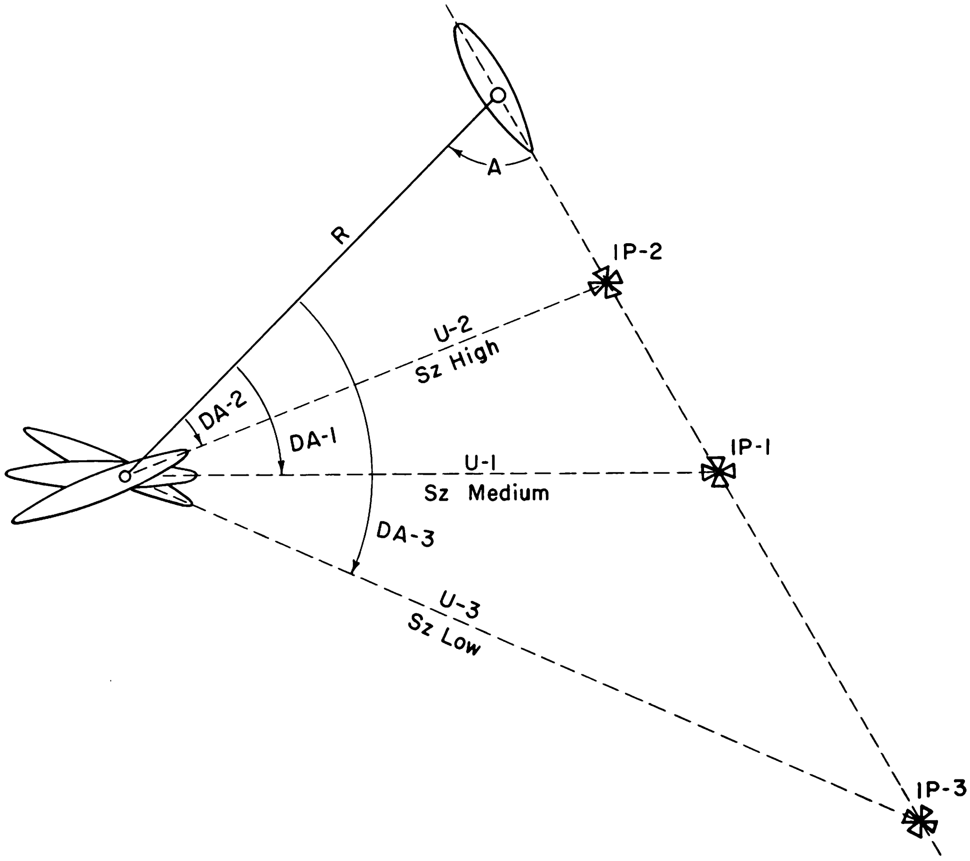


Figure 12-4.—The effect of target speed. 55.270

In the present example U also decreases. However, since Tf has decreased the effects of target motion will also decrease.

CURVED FIRE

The previous discussion has been based on the assumption that the firing submarine was aimed at the impact point at the time of torpedo launch and that the torpedo ran straight to the impact point. In practice, the torpedo leaves the tube, makes a short run, and then turns toward the impact point. This action is shown in figure 12-7. As you can see, the torpedo run has been increased. When the torpedo left the tube it was actually moving away from the impact point. Therefore, the torpedo has an additional distance to run. Also, since Tf has been increased the target advance has been increased, modifying U still further. The deflection angle has lost its significance. To determine the angle through which the torpedo must turn to reach the impact point, the computer solves for the angle between the torpedo track and the bearing line (LOS). This value is G_1 - Br and is termed the solution angle. This angle is roughly equivalent to deflection angle.

BASIC TORPEDO BALLISTICS AND CORRECTIONS

The torpedo is fired under varying conditions and at different locations in the world. These

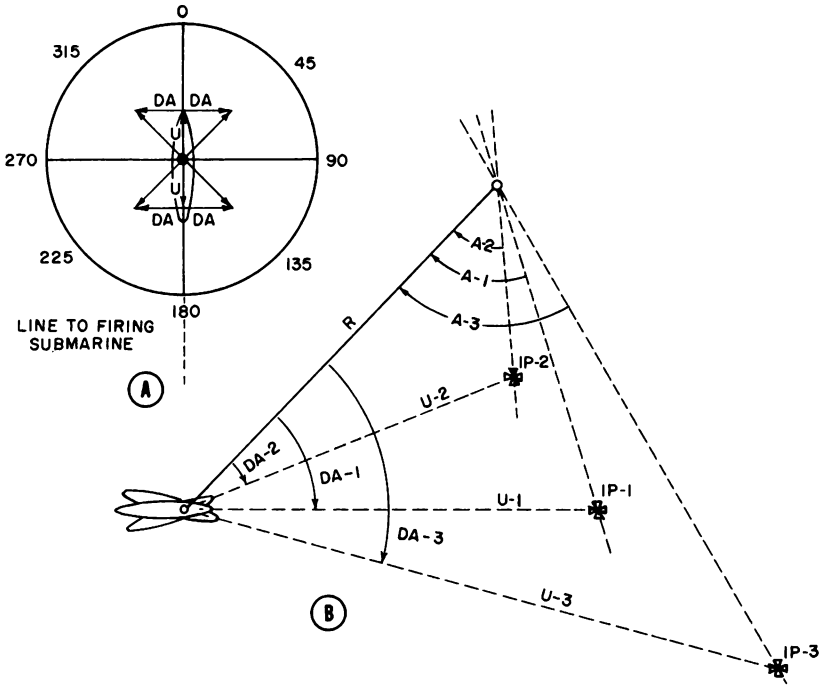


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Figure 12-5.—The effect of target angle.

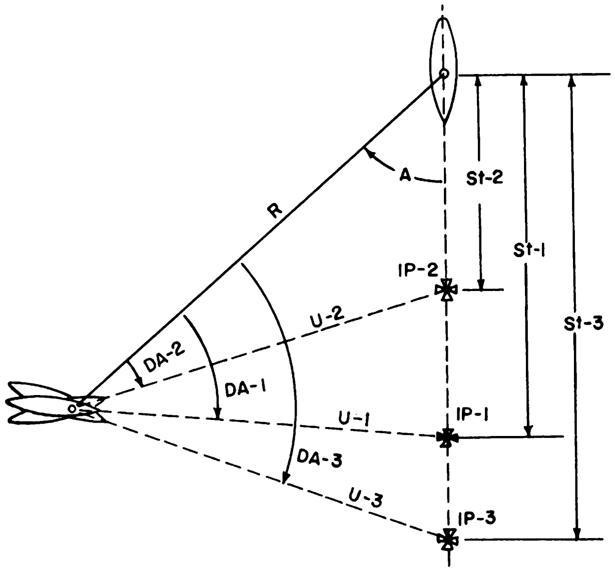

Figure 12-6.—The effect of change in torpedo speed.

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changes in environment affect its speed and direction of run. Since torpedo speed and direction are important quantities used in the computation of the fire control problem, the forces which affect the course and speed of the torpedo must be corrected for in the computer.

FORCES AFFECTING TORPEDO SPEED

The nominal speed of a torpedo is that average speed which occurs during a normal run. This run must be taken at standard depth and at standard sea water temperature.

The nominal speed of a torpedo is established at a standard sea water temperature of 62°F. As the temperature of the water changes, the pressure and density change, therefore the forces on the torpedo which affect speed must be considered.

The nominal speed of a torpedo is established at a particular running depth. If fired at a greater depth, the density of the water may be higher because of lower temperature. Therefore the torpedo will be slowed down. This decrease must be considered in the computer.

If the torpedo climbs or dives to a depth different from which it is fired, the change in depth will have an effect on its speed.

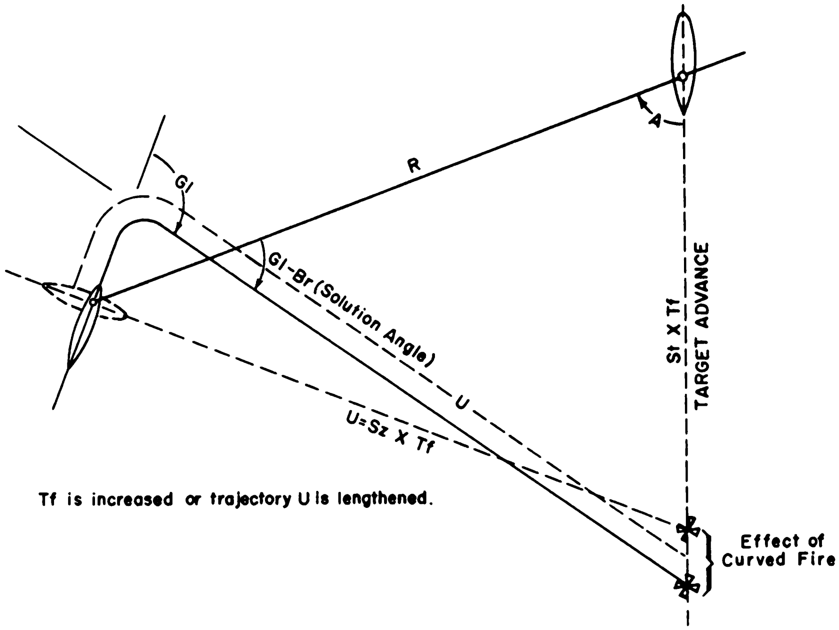

Figure 12-7.—Basic underwater fire control triangle (curved fire).

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Often a torpedo is ejected from the tube at a different speed than its final speed. It takes a definite length of time before the final speed is reached, and during that time it will cover a part of its total run. This effect of the changed speed must, of course, be considered by the computer.

FORCES AFFECTING TORPEDO COURSE

The torpedo, when in the water, is steered by a directional gyro which will retain its spin axis in a predetermined direction unless acted upon by outside forces. An angular position is set into the gyro before firing, and the rudders of the torpedo are controlled by this setting.

CORRECTIONS TO TORPEDO SPEED AND DIRECTION

Corrections to nominal speed for a particular weapon is referred to as jSz. Every torpedo is designed with a definite theoretical running speed. If, after many torpedoes have been produced and tested, this speed is found to differ from the design speed, a correction must be made before firing. Since the torpedo under actual conditions will operate at different sea water temperatures, a correction must be made for the difference between the existing temperature and the standard (62° F). A correction should also be made for the temperature of the battery electrolyte in battery-driven torpedoes. A change in the electrolyte temperature changes the power output of the battery, and that will change the torpedo speed.

Ordered Depth Correction

The symbol jSzh describes an ordered depth correction. Very often torpedoes are fired at depths other than their tested depths, as for instance when firing at another submarine. Sometimes improvements are made in a torpedo during the course of manufacture, making it possible to attain greater depths than the original designed depth. In these cases, the nominal speed of the torpedo must be changed to consider the difference between the standard depth and the actual firing depth.

Depth-Change Run Difference

Ky is the symbol for depth-change run difference (fig. 12-8). When a torpedo is fired and observed to run at a depth which is above or below the torpedo tube depth, its speed will be changed because of the effect of gravity. If a torpedo has to rise to a lesser depth, it will be

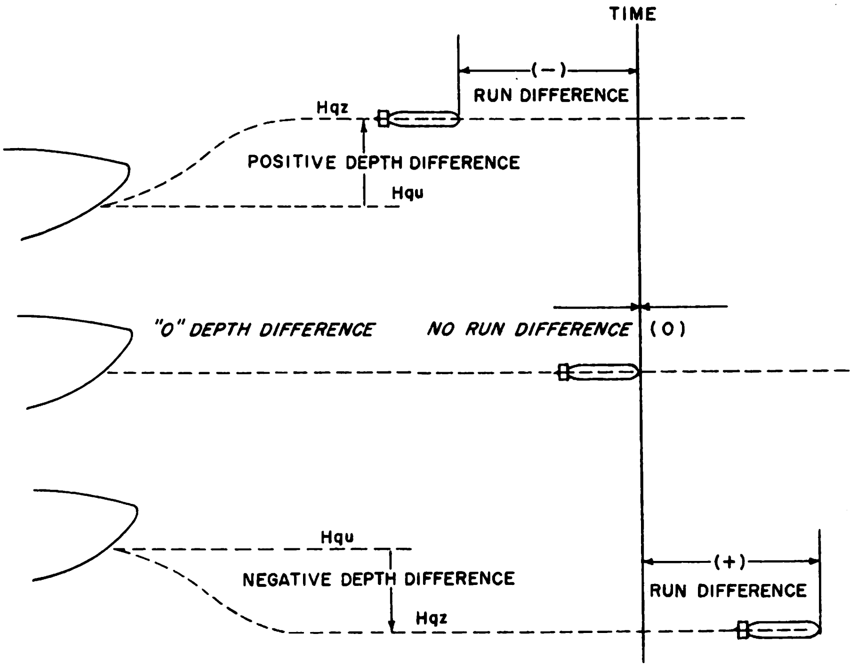


Figure 12-8.—Depth change run difference (Ky). 55.274

slowed down (just as a projectile or missile will) and cover less distance in a given period of time. On the other hand, a torpedo going down to a greater depth will be helped by gravity, and will therefore go faster and cover a greater distance.

Emergence Factors—Run Difference

Uy symbolically describes emergence factors—run difference (fig. 12-9). If a car travels at 50 miles per hour for 3 hours, it will cover 150 miles. If it went faster, it would obviously go farther in the same 3 hours. In the same way, if a torpedo emerges from a torpedo tube at a speed greater than its running speed, in a certain period of time it will go farther. This additional distance must be allowed for in the computer. On the other hand, if a torpedo emerges from the tube at a speed lower than its running speed, that is, swims out, it will cover a shorter distance in a given period of time.

DIRECTIONAL ERRORS

It was mentioned earlier that torpedoes use a gyro to provide a directional reference. A gyro, because of its momentum when spinning at a high speed, will remain directionally rigid unless acted upon by external forces. Because of this rigidity, it is used as a stable reference for torpedo azimuth (direction control).

The following discussion provides a brief review of the effect of earth's rotation on a gyro. Keep in mind that the gyro described here has its axis parallel to the earth's surface, rather than perpendicular to the horizontal as in a vertical gyro.

Now back to the torpedo's gyro. Every day the sun APPEARS to rise in the east and set in the west. It only appears this way, because the earth is rotating on its own axis from west to east, and makes a complete rotation once every 24 hours.

Since the earth rotates, while the gyro in the torpedo remains fixed in space, the direction in which the gyro seems to point changes at the rate that the earth is turning. This appears as an apparent drift (precession) of the gryro and occurs at the rate the earth is turning—15° per hour. See figure 12-10.

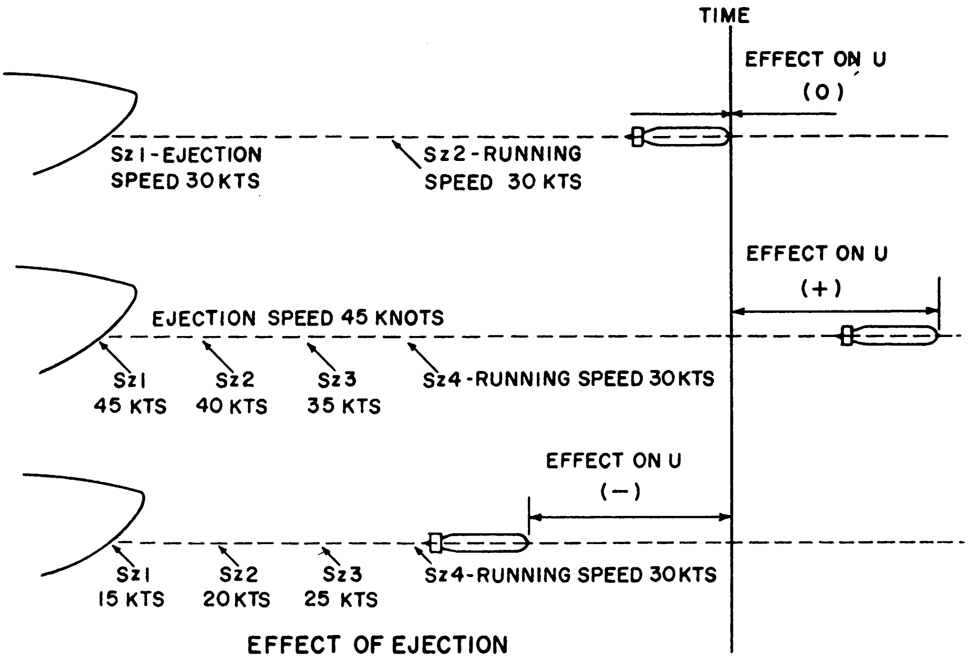


Figure 12-9.—Emergence factors—run difference.

55.275

The relative alignment of the gyro's spin axis with the earth's spin axis causes different apparent drift rates as shown in figure 12-10. The maximum effect on a directional gyro takes place at the North or South Pole, where the spin axis of the gyro is at right angles to the earth's spin axis. At the Equator, the spin axis of the gyro is parallel to the earth's spin axis, so that the rotation of the earth has no effect on the gyro. At intermediate latitudes, the earth's rate (angular velocity) effect varies as the sine of the latitude. In these cases the gyro spin axis is tilted at the angle of latitude with respect to the earth's spin axis.

Since the earth turns at a constant rate, it is possible to put a constant correction on the gyro which will cause the gyro to counteract the effect of drift at any given latitude (fig. 12-11). This correction, put into the torpedo at the test run site, is called proofing latitude.

Look at figure 12-12. Two torpedo paths are shown. In part A, a torpedo with its gyro compensated for apparent drift is aimed at point P. Point P turns with the earth from T_1 to T_2 while the torpedo is traveling toward it. The torpedo's gyro senses earth's movement and attempts to stay aligned with the space reference. However, since a correction for apparent drift has been applied to the gyro to compensate for earth's rotation it remains directed toward point P. Therefore the torpedo travels a straight path to point P.

In part B of figure 12-12 the same situation is illustrated. Now, however, an uncompensated gyro is steering the torpedo. The gyro will sense earth's rotation and apparently precess to remain aligned with the space reference. The torpedo will follow a curved path with respect to the earth and will miss point P. This curved path is typical of many fire control firings and introduces the need for latitude corrections which can be inserted into the computer to adjust gyro angle accordingly.

The corrections are detailed in figure 12-13. A difference of latitude between firing and proofing causes the torpedo to turn away from the impact point during torpedo run. At the end of the run, the torpedo will have a heading difference equal to the drift rate of the gyro (DjGm) times the time of flight (Tf). If an imaginary effective path from own ship to the end of U is drawn along with a line tangent to the curve at the end of the actual U and extended back across the calculated U (straight), a triangle is formed. The heading difference will be equal to twice the latitude error angle (angle between the calculated track and effective path). Since Gm (latitude

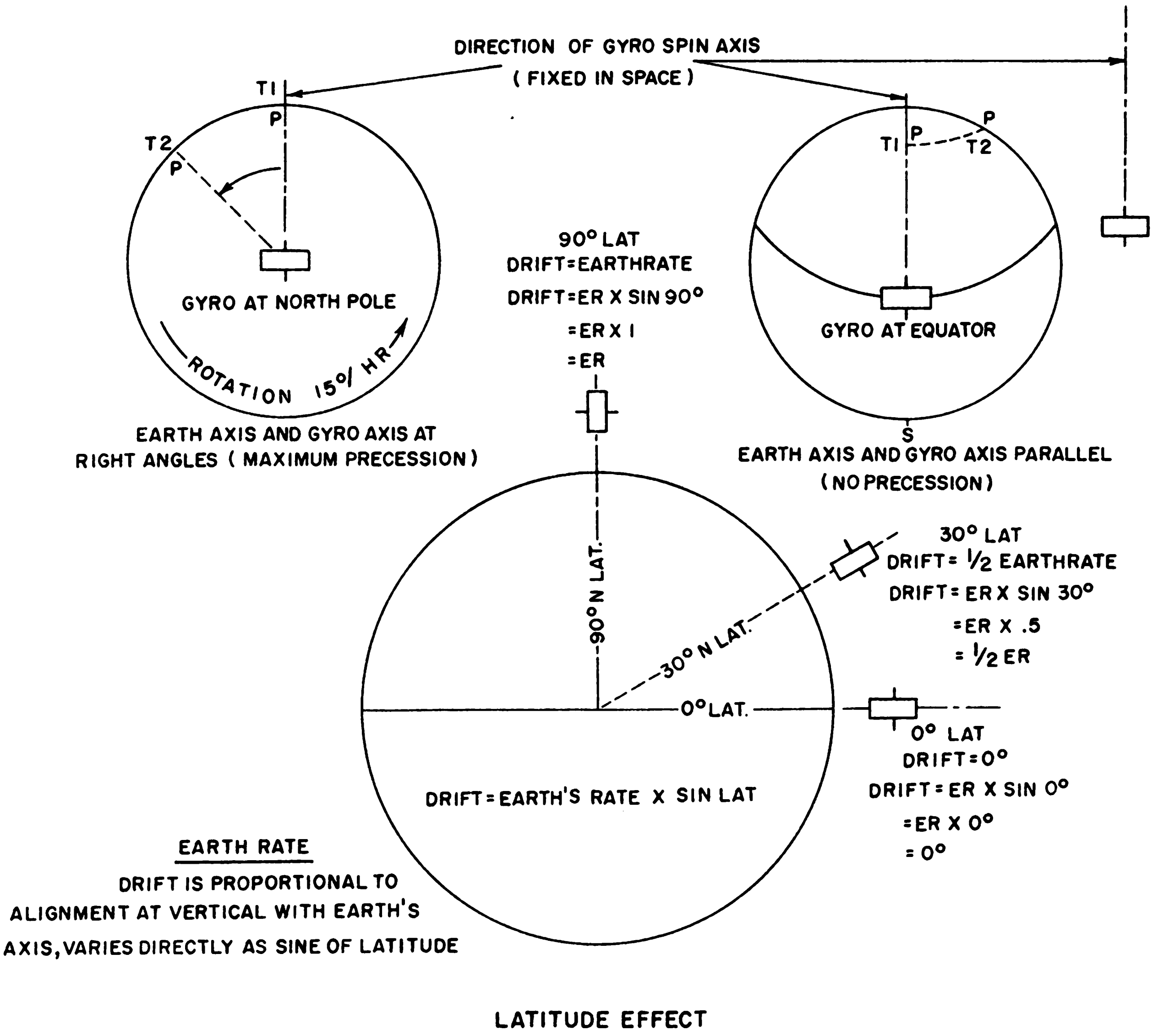


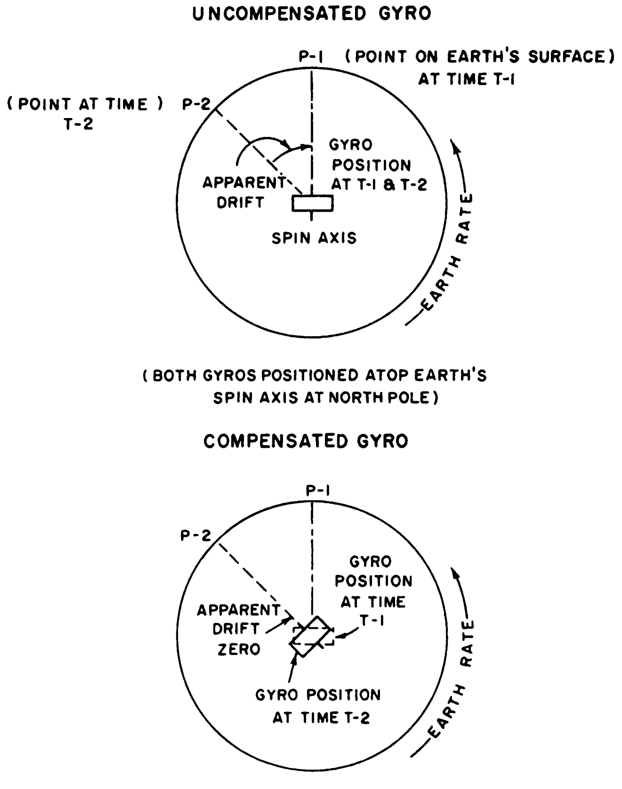
Figure 12-10.—Gyro drift (apparent precession). 55.276

correction) must balance out the latitude error, it follows that $G_m = 1/2 D_j G_m \times T_f$.

Figure 12-14 shows a typical shot with latitude correction (Gm) inserted into the fire control problem to balance out latitude error. Note that latitude correction changes DA by an amount equal to latitude error.

BASIC TORPEDO TRAJECTORIES

A knowledge of the basic torpedo trajectories will help you toward a better understanding of the general submarine fire control problem. The basic fire control problem as explained previously, involves a preset, straight running torpedo as shown in figure 12-15. The diagram displays information describing the target position related to own ship. This information is Br, R, and A. The target advance is shown in figure 12-15, by St· Tf. Information related to the target is referenced to the fire control reference point on own ship. The torpedo tubes are forward of the reference point by a distance P1. The torpedo is launched from the tube and runs straight, a distance M called the REACH DISTANCE. It then turns through an angle (G_1, the


UNCOMPENSATED GYRO
P-1 (POINT ON EARTH'S SURFACE) AT TIME T-1
(POINT AT TIME T-2) P-2
GYRO POSITION AT T-1 & T-2
APPARENT DRIFT
SPIN AXIS
EARTH RATE
(BOTH GYROS POSITIONED ATOP EARTH'S SPIN AXIS AT NORTH POLE)
COMPENSATED GYRO
P-1
P-2
GYRO POSITION AT TIME T-1
APPARENT DRIFT ZERO
GYRO POSITION AT TIME T-2
EARTH RATE

55.277

Figure 12-11.—Compensation effect on drift.

gyro angle) with a turn radius of Z_1, and runs straight to the impact point. The angle between the torpedo track and the bearing line is G_1 - Br, the solution angle. The angle between the target track and the torpedo run is designated I and is called the impact or track angle which is equal to G_1 - Br + A.

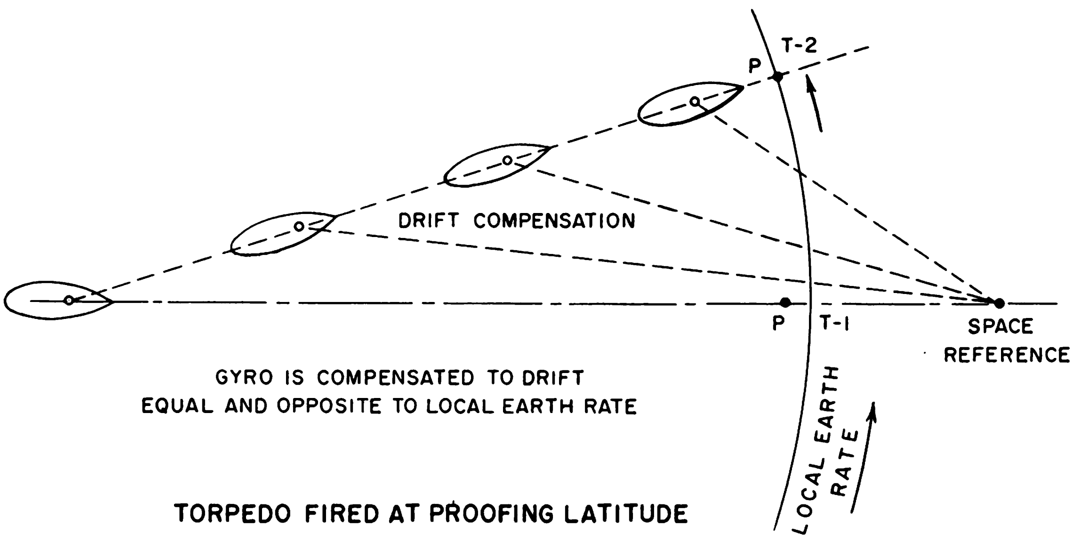
Another type of torpedo is the homing torpedo. As shown in figure 12-16 this torpedo will search for the target by SNAKING, that is, turning left and right in order to "hear" the target. It is desirable to have this type of torpedo enable, that is, start to search, before crossing the target track. To accomplish this the fire control problem is solved in the normal way for U. Then a value of Ue off. (enabling run offset) is subtracted from it and transmitted to the torpedo. This will cause the torpedo to enable before crossing the target track with the torpedo aimed at the intercept point. Except for Ue offset, then, the trajectory for a homing torpedo is the same as for the straight run shot previously described.

Some torpedoes turn a second time when they are close to the target. The second turn has two advantages: (1) the torpedo may cross the target track twice increasing its opportunities to detect the target, and (2) the angle at which the torpedo crosses the target track is improved. Consider a case where the target is coming toward you. A preset straight running torpedo sees only the width of the target. However, a second turn torpedo can turn and cross the target track at right angles. It sees the length of the target and as a result has a higher hit probability.

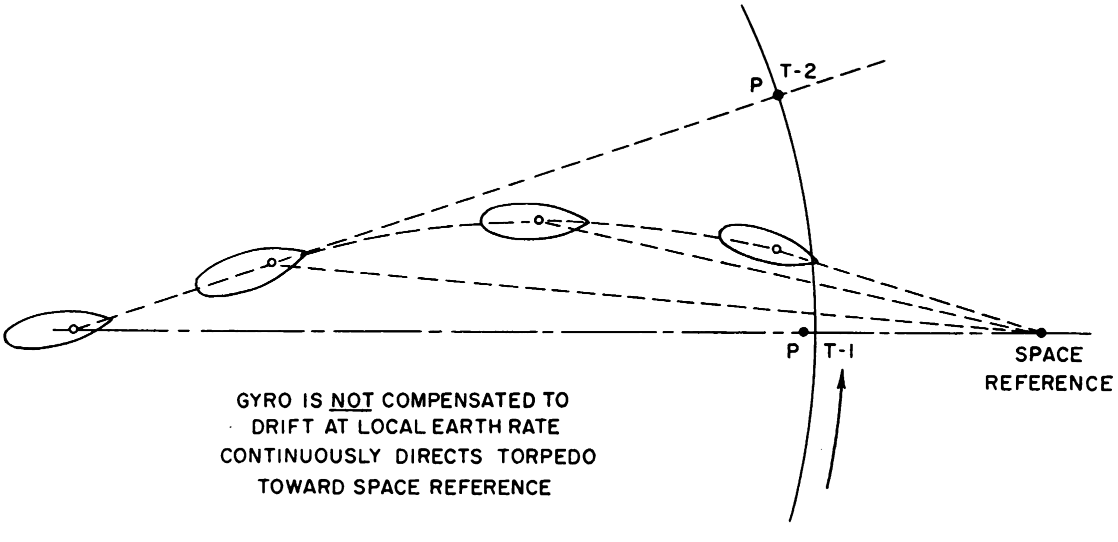
Sometimes it is desirable to fire torpedoes in salvos. In this case they are not fired all at the same point. To allow for errors in our knowledge about the target, or for possible changes in target course and speed, the torpedoes are fired in a pattern. One such pattern is linear spread. A unit of linear spread is selected for each torpedo. A number of units is selected either fore or aft. Look at figure 12-17. Here three impact points are shown. The center impact point is the one for no linear spread. Liu on the diagram represents the distance selected for a unit of spread. The impact point further along the target track represents the impact point with two units of spread forward in the computer. Notice that linear spread is put in along the target track. Both gyro angle and torpedo run are changed by linear spread. Linear spread clearly will increase hit probability if there is an error in estimating target speed.

Another type of salvo pattern is called angular spread. As with linear spread, a unit of spread is selected. Then for each torpedo, a number of units is selected either right or left. See figure 12-18. The spread angle is added or subtracted to gyro angle after a solution has been reached. As a result, the torpedo run (U) is unchanged. Angular spread is a correction across the torpedo track. Linear spread is a correction along the target track. Either correction is intended to allow for errors in the knowledge about the target or for errors in the torpedo.

Torpedoes which can be ordered to run at a certain depth and then search for a target by acoustical means may be dangerous to own ship should own ship be at or near the search depth. Torpedoes are instructed to search above or below a certain depth, called stratum depth. If own ship is in the depth range in which the torpedo will search, then the computer will give a warning to this effect. Refer to figure 12-19. Do is the depth of the keel of own ship. A torpedo which will search below a certain depth is


T-2
P
DRIFT COMPENSATION
P
T-1
SPACE REFERENCE
GYRO IS COMPENSATED TO DRIFT
EQUAL AND OPPOSITE TO LOCAL EARTH RATE
LOCAL EARTH RATE

TORPEDO FIRED AT PROOFING LATITUDE


T-2
P
P
T-1
SPACE REFERENCE
GYRO IS NOT COMPENSATED TO
DRIFT AT LOCAL EARTH RATE
CONTINUOUSLY DIRECTS TORPEDO
TOWARD SPACE REFERENCE

TORPEDO FIRED AT OTHER THAN PROOFING LATITUDE

Figure 12-12.—Effect of gyro drift on torpedo course. 55.278

referred to as a torpedo running below stratum. In this case, a safety factor is added to own depth and any depth below this is considered safe. A torpedo which will search above stratum depth is referred to as a torpedo running above stratum. In this case the height of own ship (plus a safety factor) is subtracted from own depth to determine the safe level of search.

It can be seen that the torpedo's search pattern is limited by stratum depth. The stratum establishes the upper or lower depth at which the torpedo will search. The depths between which the torpedo will search is called stratum limit.

EVOLUTION OF UNDERWATER FIRE CONTROL SYSTEMS FROM WW II TO PRESENT

The solution of the underwater fire control problem requires that relative position (range

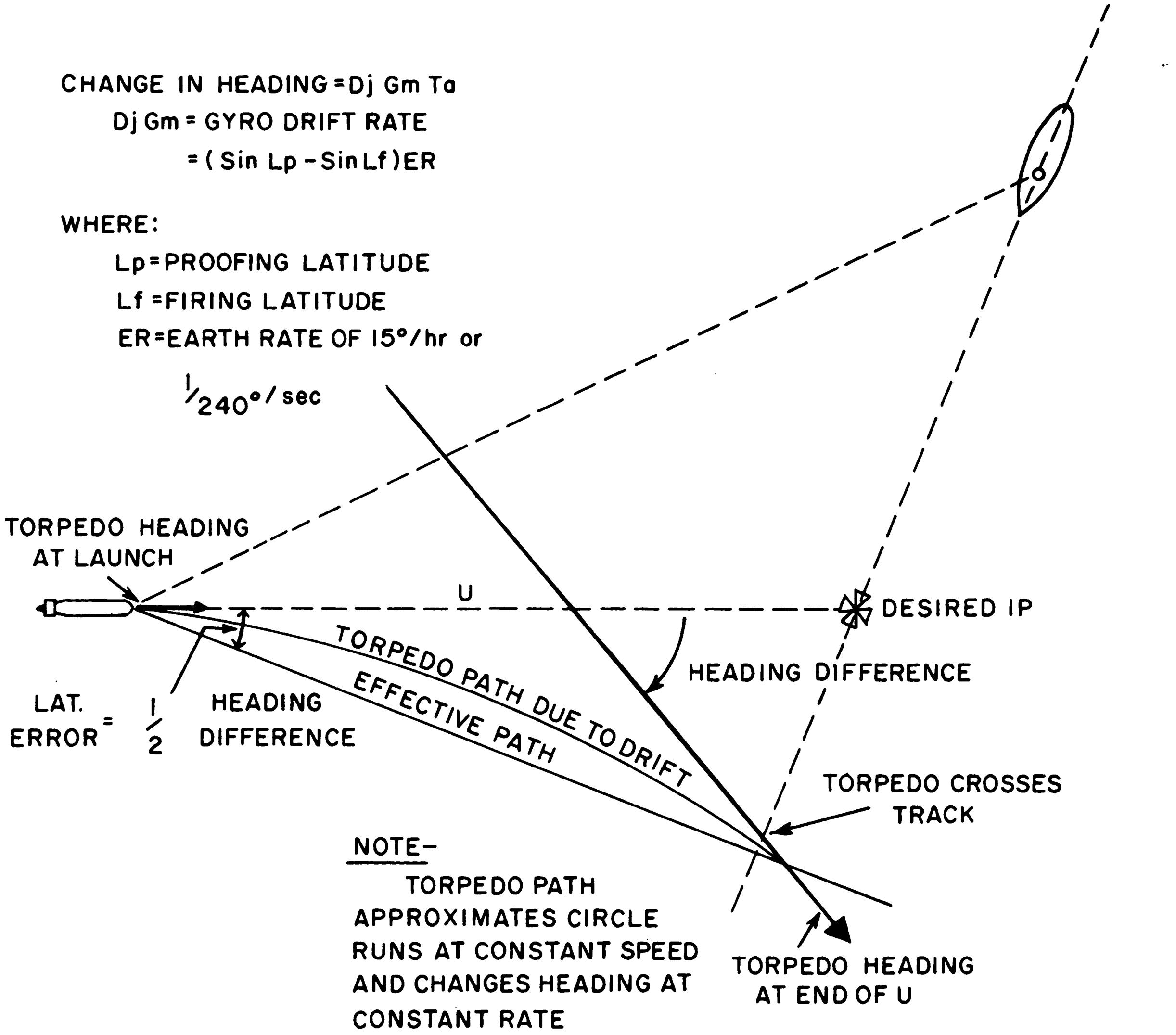
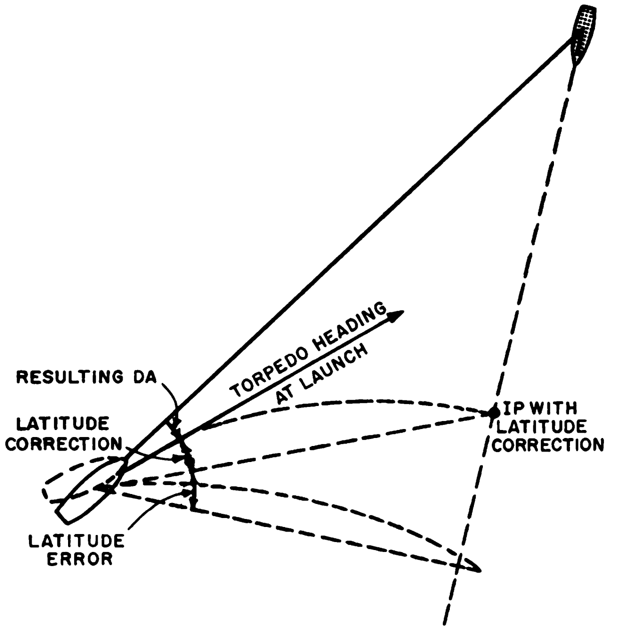

CHANGE IN HEADING = Dj Gm Ta
Dj Gm = GYRO DRIFT RATE
= (Sin Lp - Sin Lf) ER
WHERE:
Lp = PROOFING LATITUDE
Lf = FIRING LATITUDE
ER = EARTH RATE OF 15°/hr or
1/240°/sec
TORPEDO HEADING AT LAUNCH
U
DESIRED IP
TORPEDO PATH DUE TO DRIFT
EFFECTIVE PATH
HEADING DIFFERENCE
LAT. ERROR = 1/2 HEADING DIFFERENCE
TORPEDO CROSSES TRACK
NOTE–
TORPEDO PATH APPROXIMATES CIRCLE RUNS AT CONSTANT SPEED AND CHANGES HEADING AT CONSTANT RATE
TORPEDO HEADING AT END OF U

Figure 12-13.—Latitude difference effect on torpedo course. 55.279

and relative bearing), course, and speed of the target be determined so that relative torpedo course (gyro angle) can be computed to direct a torpedo to an intercept point along the target track. The determination of target information is complicated because, in general, only intermittent observations of the target are possible. The problem of position keeping is solved by using the technique of setting up a phantom problem just as we do in a surface fire control rangekeeper or computer. This technique provides the continuous information needed for the computation of the lead necessary to hit a moving target.

Before computers came into use, plots and slide rule devices were used to determine the torpedo course necessary to hit the target. This method placed limitations on how the attacking submarine could maneuver because the solution had to be worked out in advance of the actual firing. The submarine was then maneuvered to the proper position and heading (proper lead angle) and waited until the target reached a certain point along its track before firing the torpedo. This procedure, necessary with nonsteerable torpedoes, was continued in use where steerable (but not always reliable) torpedoes were fired with zero gyro angles.

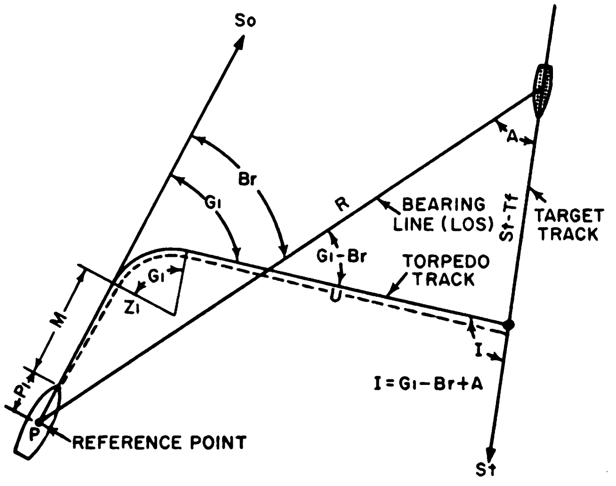
The need for continuous (sometimes the term synchronous is used) solutions to take advantage of the steerable torpedoes led to the development of computers. With continuous solutions, the



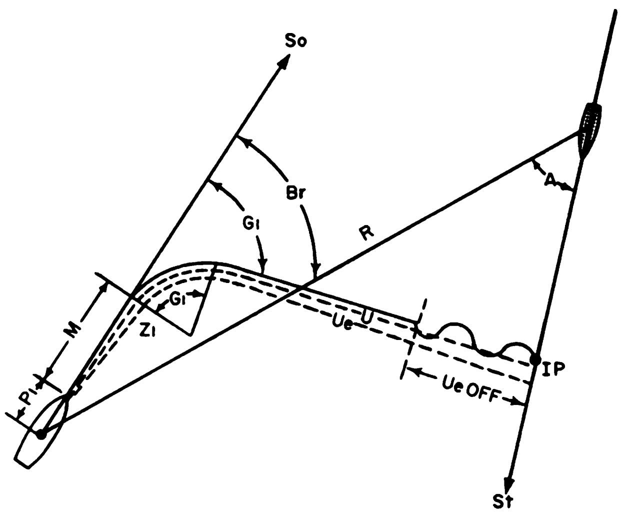
55.280
Figure 12-14.—Effect of latitude correction.

submarine was freed of the necessity of being in a particular place, at a particular time, on a particular heading, to launch a torpedo. Torpedoes could now be launched if the target data was considered reliable and the run within the torpedo capabilities.

Electrically set torpedoes further eased the problems of launching because the weapons could be made to follow continuously (synchronously)



55.281
Figure 12-15.—Preset torpedo on a straight run.



55.282
Figure 12-16.—Preset torpedo on a homing run.

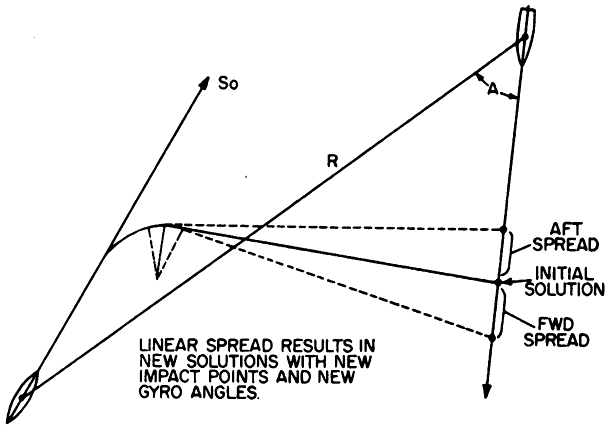

So
A
R
AFT SPREAD
INITIAL SOLUTION
FWD SPREAD
LINEAR SPREAD RESULTS IN NEW SOLUTIONS WITH NEW IMPACT POINTS AND NEW GYRO ANGLES.

Figure 12-17.—Preset torpedo with linear spread.
55.283

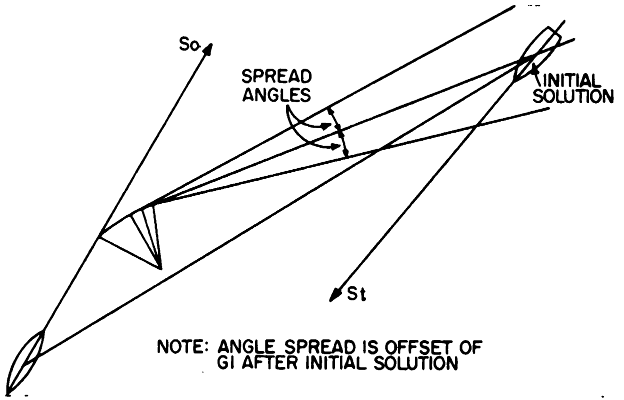
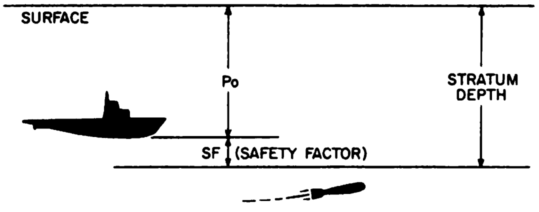
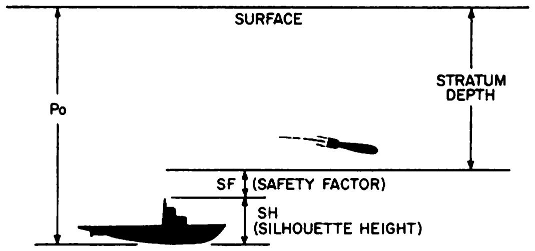


Figure 12-18.—Preset torpedo with angular spread.
55.284



TORPEDO RUNNING BELOW STRATUM



TORPEDO RUNNING ABOVE STRATUM

Figure 12-19.—Stratum relationships. 55.285

the solution generated in the fire control system. Thus, a correct solution is in the torpedo at any instant.

Homing torpedoes further freed firing submarines of restrictions because less exact solutions could be used and the homing capability of the torpedo would compensate for the solution errors. However, homing torpedoes had to be programmed before firing and a means of inserting these instructions (preset instructions) had to be incorporated into the fire control system.

Along with torpedoes, the development of detection equipment, gyrocompasses, and other sensing devices has had its effect on the evolution of underwater fire control equipment. Most notable is the need for converters of sonar information. Such converters for sonar bearings appeared in the earliest submarine fire control computers, called target data computers (TDC). There are several reasons why sonar data conversion is necessary. First, sonar bearings and ranges are measured from the point at which the sonar head is located. This point is displaced from the fire control reference center on most ships. The effect of this displacement on sonar range and bearing will vary as a function of relative target bearing.

Another factor affecting passive sonar data is the distance measured from the target sound source (screws) to the center of the target. This distance is dependent on target size and varies as a function of target angle.

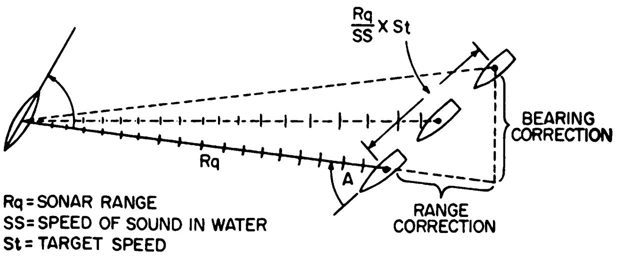
A final factor affecting sonar measured quantities is target advance. Figure 12-20 illustrates how target advance combined with sonar range in yards divided by the speed of sound in water times target speed varies as a function of target angle (A).

The series of fire control systems described below shows how the evolution of the systems paralleled the evolution of the weapons.

The first of the underwater fire control computers was the TDC mentioned previously. Figure 12-21 is a block diagram of the TDC Mk 4. The TDC is a position keeper and a gyro angle solver. In fact, it has two angle solvers which provide separate solutions for the forward and after torpedo tubes simultaneously. Even in this early computer a sonar bearing converter is provided. Gyro angle is transmitted electrically to the torpedo room, but it must then be inserted mechanically into the torpedo.

The TDC had certain functions added to it and became the FCS Mk 106 Mod 5 (fig. 12-22). In this system, gyro angle is transmitted continuously to the electrically set torpedoes. Enabling run and ordered depth are transmitted electrically to the torpedo. The insertion of preset functions for homing torpedoes is made at a control panel. The automatic transmission of synchronous functions requires a monitoring system to indicate whether or not the torpedo is actually accepting the synchronous inputs.

The FCS Mk 101 Mod 9 was the first attempt to integrate all functions of the fire control effort into a self-sufficient system. The addition of a target analyzer made possible the direct determination of target course and speed by the



TARGET ADVANCE = PARALLAX DUE TO TARGET MOTION DURING SOUND TRANSIT. VARIES AS A FUNCTION OF A.

Figure 12-20.—Target advance affects sonar data. 55.284

fire control system by using sensor and own ship data. The system also provided for the input of linear spread and the insertion of torpedo and tube orders.

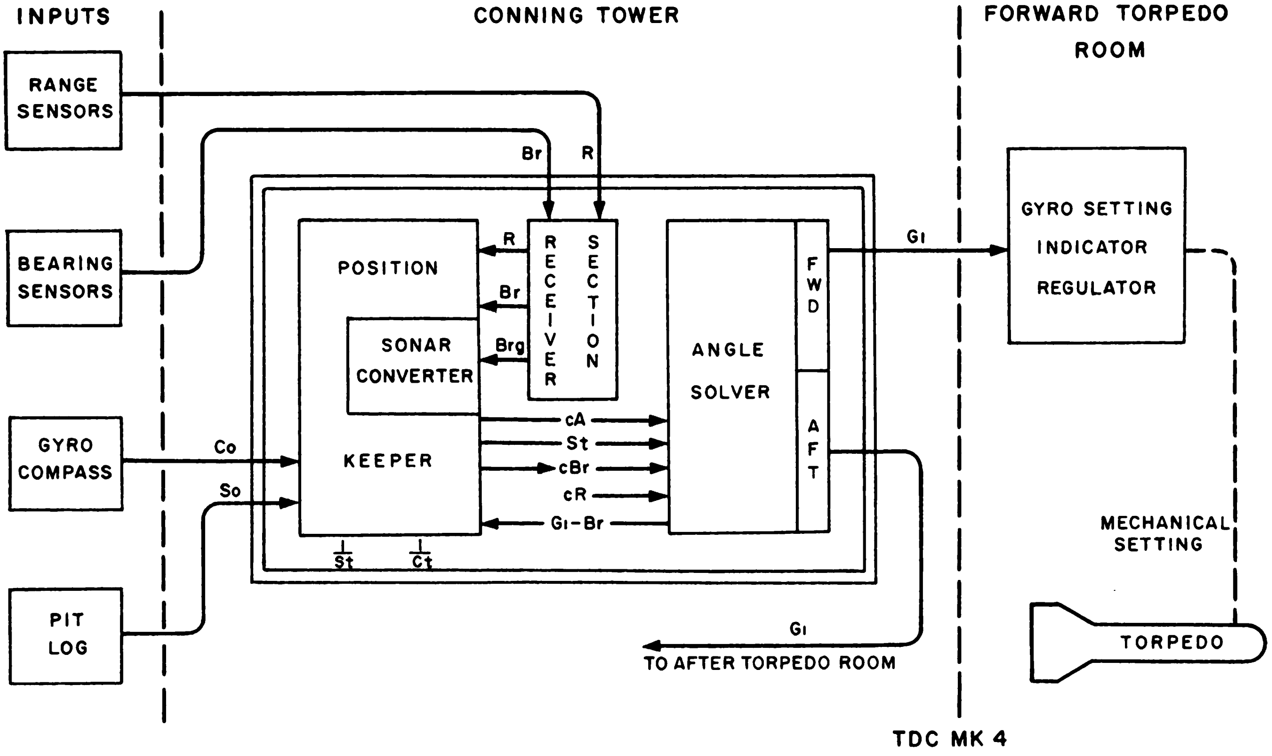


Figure 12-21.—Torpedo data computer simplified block diagram.

55.287

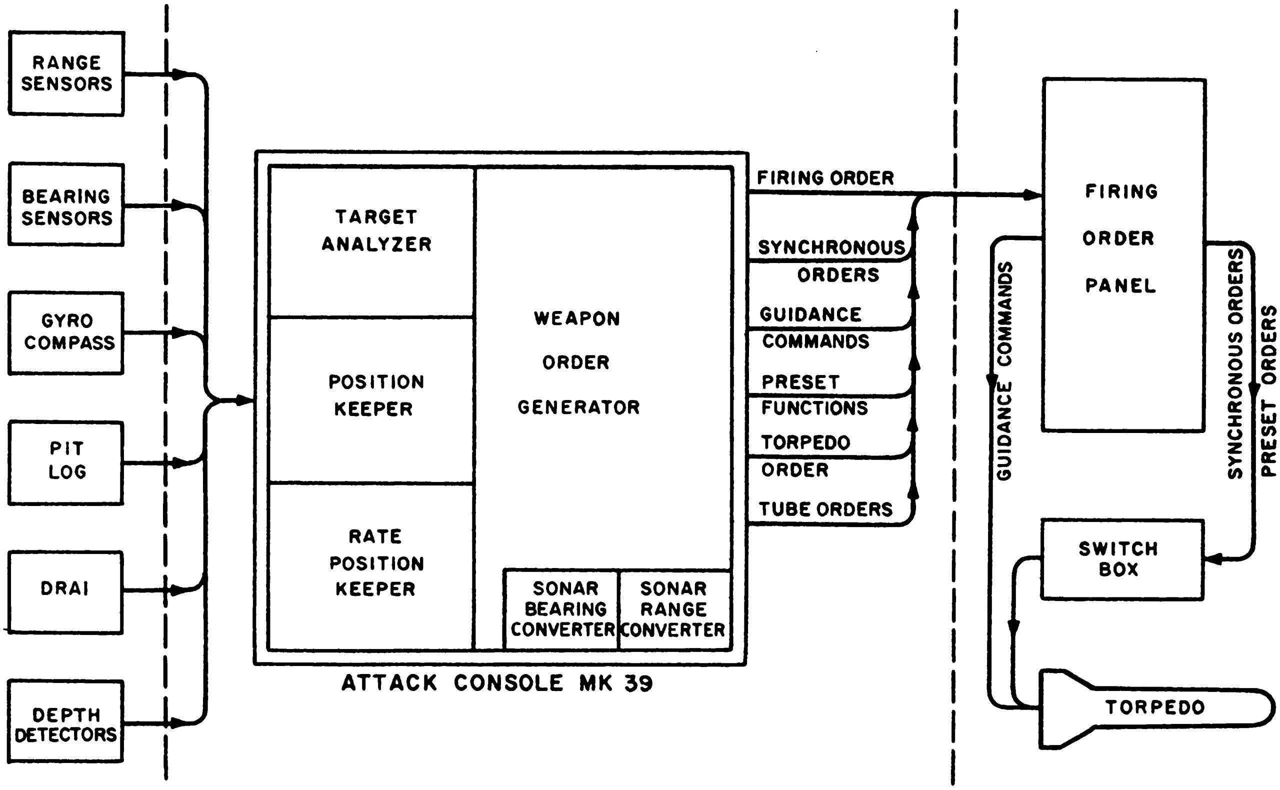


Figure 12-22.—Submarine fire control system simplified block diagram. 55.288

CHAPTER 13

RANGEFINDERS

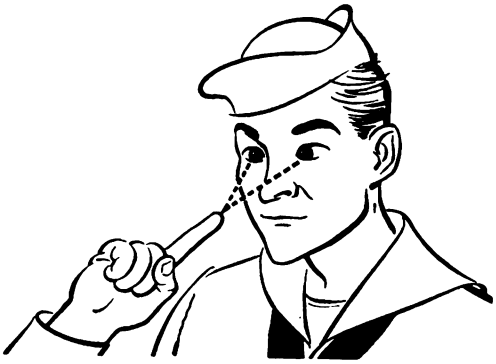
Rangefinders are optical instruments used to determine the distance to an object. In fire control, the rangefinder, as the name implies, is used to measure the range to a target. The rangefinder extends and improves the performance of your own built-in rangefinder. Every man with two eyes and normal vision has a built-in rangefinder. The eyes and brain working together have learned to sense distance or depth. This sensation is called depth perception or stereoscopic vision.

This chapter covers briefly the principles of depth perception used by the stereoscopic rangefinder. This type of rangefinder is a binocular device, which means simply that both eyes are used. A comprehensive coverage of stereoscopic vision is given in OP 556, Optical Equipment.

STEREOSCOPIC VISION

In normal vision a slightly different view is presented to each eye. To confirm this, you have only to view the objects in the immediate vicinity first with one eye and then with the other, and note the sidewise shift of the nearby objects relative to the fartherest ones. This lateral shift is caused by the fact that the eyes are spaced laterally, and thus occupy different viewpoints. In order to see an object singly and sharply with two eyes, the lines of sight from both eyes must fix the object. In other words, the two lines of sight must intersect at the object being observed. The angle formed by this intersection is called the angle of convergence. The value of this angle is determined by baselength and the distance to the observed object. The baselength is the distance between your eyes, and is called interpupillary distance. For any given baselength, the angle of convergence depends only on the distance to the observed object.

You can easily demonstrate the different angles of convergence by a simple experiment. Hold your arm straight, and raise your index finger. Now move the finger slowly toward your nose, keeping both eyes on it. By the time the finger reaches your nose, the lines of sight from your eyes to your finger converge sharply (fig. 13-1).



55.289

Figure 13-1.—Angleof convergence.

Next, look at some distant object. Now the lines of sight from your eyes are almost parallel.

Obviously, then, the closer the object, the greater the convergence; the farther away, the more nearly parallel the lines of sight become. The brain gives us an impression of the position of an object by comparing its angle of convergence with that of a second object. Each angle of convergence is associated with a definite object distance.

LIMITING FACTOR

There is a limit to detectable differences in the angle of convergence, and therefore to stereoscopic vision. When two angles of convergence are very nearly the same, the unaided eyes can see no difference between them.

Magnification of the field of vision will increase the ability of the eyes to distinguish the differences in angles of convergence. Assume an optical system with a magnification of M. It will increase all visual angles M times, and it follows that the perception of distance is made M times as acute.

The distance of an object is determined by baselength and the angle of convergence. Since your eyes are spaced close together, the baselength is small and the angle will be small. Therefore, accurate depth perception, even with magnification, is limited to relatively short distances. An increase in baselength will increase the apparent difference between the convergence angles of any two objects, and thus make your stereoscopic distance determination more acute. This increase in baselength is accomplished by the rangefinder. The apparent angle of convergence is also called the PARALLACTIC ANGLE.

STEREOSCOPIC RANGEFINDER PRINCIPLES

The stereoscopic rangefinder improves our depth perception in two ways—by magnifying the image, and by increasing the baselength. In the rangefinder, these two things are accomplished in a linear manner, so that the relationship between all objects and all dimensions remains constant. The improvement in stereoscopic vision is equal to the product of the ratio of baselength increase and the power of magnification.

TRIANGULATION

The rangefinder is essentially an analog computer. It uses optical devices to solve a right triangle problem, and in so doing determines the range to a target. This method, called triangulation, is widely used to determine distances that cannot be measured directly. Figure 13-2 illustrates the principle of triangulation. If you are at point A, and you want to know the distance to point P, you measure off the distance AB at right angles to AP. At point B you measure the angle θ between BP and the line BC, which is parallel to AP. Since BC and AP are parallel lines cut by the transversal BP, the alternate interior angles APB and θ are equal. Then you have $\tan \theta = \frac{AB}{AP}$. From this formula, you can calculate the length of line AP.

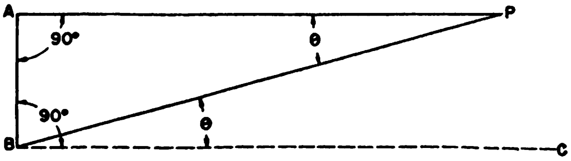


Figure 13-2.—Measuring distance by triangulation. 55.290

The distance AB is called the base, and is written B. In our problem, B represents the baselength of the rangefinder, and therefore is a fixed, known distance. The distance AP obviously would be range R. The triangular formula can be written $\tan \theta = \frac{B}{R}$.

The illustration in figure 13-2 was drawn out of proportion for clarity. Actually range R is long compared to base B, and the parallactic angle θ is small. For small angles, the tangent of the angle varies in a nearly linear manner with the angle. Thus the rangefinder can solve directly for R by measuring the angle θ. The rangefinder formula can be written $\theta = \frac{B}{R}$.

The rangefinder measures the angle θ by use of optical elements that deviate the line of sight from point B through a variable angle. The movable elements are connected to a suitably calibrated scale. The position of the scale depends on the angle through which the line of sight from point B has been deviated. The scale is calibrated in yards, and you can read the range directly from the scale when the lines of sight from A and B intersect at the target.

First we will see how we can increase the baselength, next how the field of vision is magnified, and finally how we can measure the deviation of one of the lines of sight to obtain a range reading. It is not the purpose of this chapter to explain the science of optics, but only to explain the function of the optical elements found in a stereoscopic rangefinder.

SPREADING THE EYES

This is how you can "spread your eyes apart" with a rangefinder. A penta (5-sided) prism will turn a ray of light exactly 90°. Suppose you took a stiff metal bar, 15 feet long, and mounted a penta prism at each end. Turn the bar toward a distant object so that a line from the left-hand prism to the object is perpendicular to the bar as in figure 13-3 (left-hand prism is upper one in this figure).

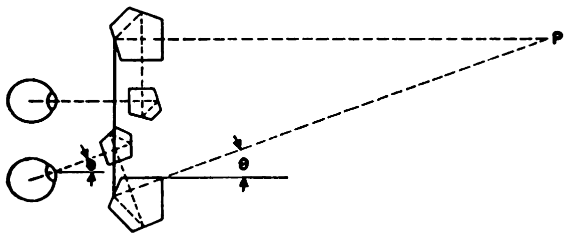


Figure 13-3.—How to increase the baselength of the eyes. 55.291

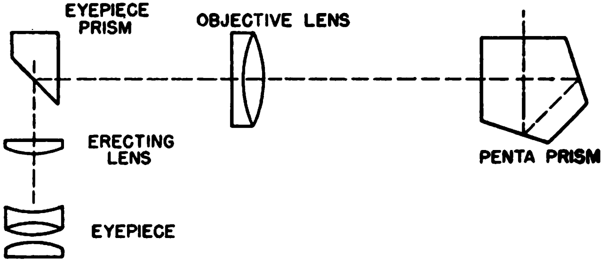


Figure 13-4.—Simple telescope. 55.292

The ray of light from the distant target to the left prism will be turned 90° and will travel inward along the bar and parallel to it. But a ray from the target to the right (lower) prism will make a rather large parallactic angle with the bar—more than 70 times the parallactic angle which the eyes would see at the same distance. This second ray will be reflected in along the bar, too, but will make an angle θ with it.

An additional pair of penta prisms could be used as shown in figure 13-3, or some other arrangement of mirrors and prisms could be used at the center of the bar, spaced as far apart as the eyes, to complete the "rangefinder." This arrangement would again turn each ray through 90°, directing each into one of the eyes. These two rays enter the eyes divergent by an amount equal to the parallactic angle θ, an angle which results from a 15-foot base rather than the short distance between the eyes. Thus, your eyes would see the object with the same parallactic angle as if you had spread your eyes 15 feet apart. This increases the maximum distance at which the eyes can detect differences in range by more than 70 times. The increased rangefinding ability can be found by dividing 15 feet by the distance between your eye pupils.

MAGNIFICATION

A telescope provides an enlarged image of a distant object. The main optical system of a rangefinder is in effect two telescopes with equal magnification. This arrangement is similar to a pair of binoculars, but with a greater increase in baselength. Figure 13-4 shows the optical system of one of the telescopes.

The rays of light from a distant target are reflected at a fixed angle by the penta prism. When the reflected rays coincide with the axis of the instrument, the target is in the center of the field of vision.

The objective lens forms a real image of the distant target. Since rays diverge from this real image just as they do from the target itself, you can examine the real image and see a magnified view of the target. However, the real image is inverted.

The eyepiece prism reflects the real image 90° into the erecting lens. The erecting lens is a second objective lens. Thus the target is inverted twice, and will appear erect or right-side-up when seen through the eyepiece. The eyepiece assembly, which is also referred to as the ocular assembly, serves as a magnifying glass. Through it you can see an enlarged virtual image of the real image formed by the objective lens.

The parallactic angle, already increased by the increase in baselength, is multiplied again by the magnifying power of the rangefinder. Thus, for example, a rangefinder with a 15-foot base and a 24-power magnification factor would have about 1700 times the range sensitivity of the unaided eye. The figure 1700 is arrived at by dividing interpupillary distance (which varies from 58 to 72 MM and averages 65 MM or about 2.5 inches) into the base of the rangefinder (15 feet), and multiplying this answer (72) by the magnification factor (24). Naturally, the answer will vary with a change of interpupillary distance.

The addition of the lenses in figure 13-4 magnifies the parallactic angle by an amount M. This changes the rangefinder formula to $\theta = \frac{BM}{R}$, where B and R are expressed in yards.

MEASURING RANGE

So far, you have an excellent spotting glass. That is, an operator can tell very accurately which of two distant objects is farther away. But he still can't tell just how far away either object is. To measure distance, another unit must be introduced into the instrument.

The Measuring Wedge

In figure 13-5, a thin refracting prism, or measuring wedge, has been inserted in the right-hand side of the instrument. A ray of light is coming from the penta prism making an angle θ with the axis of the rangefinder. This angle is the parallactic angle.

When the ray enters the thin prism it will be bent toward the thicker edge of the prism. The prism reduces the angle between the ray and the axis of the instrument. To an operator looking through the eyepieces, the target would appear to have moved farther away.

If the prism has just the right thickness, the ray of light will be bent parallel to the axis of the instrument. You can see that for every parallactic angle—i.e. for every distance—there will be a particular prism which will bend the rays exactly parallel to the axis.

The operator can measure the parallactic angle, and the corresponding distance, by seeing just how thick a prism he needs to bring the ray parallel to the axis. In other words, the prism he needs to reduce the parallactic angle to zero.

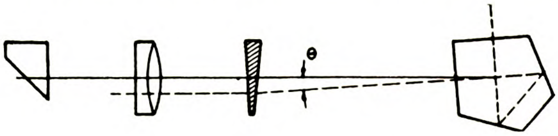


Figure 13-5.—Measuring wedge. 55.293

But how is the operator going to tell when the ray is parallel to the axis? At the focal plane of the objective lens on each side of the instrument is located a reticle on which several sets of reference marks are engraved, as shown, in figure 13-6. These reference marks are called the WANDER MARKS, or RANGING MARKS. These marks are the diamond shaped images in the center of the reticles. The large center diamond is used for ranging on the target. The ranging marks are on the optical axis of each side of the rangefinder. The operator sees the ranging marks in each eye, but they are blended stereoscopically to form a single impression with a definite parallactic angle. This angle is fixed by having the optical axis of the left side 90° from its line of sight; while the optical axis of the right side is at an angle somewhat less than 90° from its line of sight. Thus the ranging marks are positioned to form a parallactic angle, and the reticle pattern appears to lie at a certain fixed distance in space.

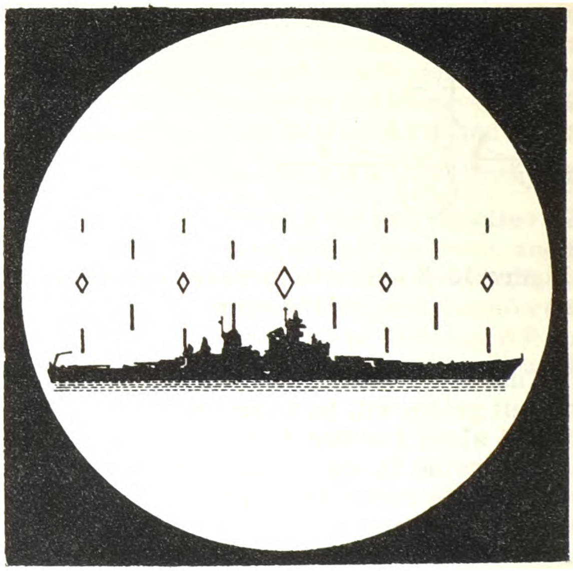


Figure 13-6.—Reference marks. 55.294

Now if the angle between the rays coming from the two RANGING MARKS is less than the parallactic angle between the rays from the target, the mark will appear to the observer to be more distant than the target. But if the angles are the same, the target and ranging mark will appear to be at the same distance. Therefore, when the ranging mark and the target appear to the operator to be at the same distance, he knows that the rays from the target have been bent by the measuring wedge enough to make them parallel to the axis of the instrument.

Operation of the Measuring Wedge

A rangefinder operator would be a busy man if he had to try out several different prisms in order to measure a range, so a convenient way of varying the amount by which a single refracting prism bends the light is provided by rotating the prism or MEASURING WEDGE.

If the prism is rotated with its thick edge up, as in figure 13-5, the ray will be bent forward or backward. Now if the prism is turned 90°, it will bend the ray just as much, but the bending will all be up and down with no forward and backward bending.

If the prism is turned to some angle a in between the vertical and horizontal, the bending will be partly up and down, and partly forward and backward as shown in figure 13-7.

In figure 13-7, the ray passing through the prism has been projected onto a screen to show the amount of bending. On the screen, AO measures the total amount by which the prism bends the ray. It will have the same length for any position of the prism. OC measures the amount of forward and backward bending and its length will depend upon the rotation of the prism. It is only the forward and backward bending that affects the apparent distance of the target. Rotation of the prism enables the operator to bend the ray forward and backward by any amount he desires.

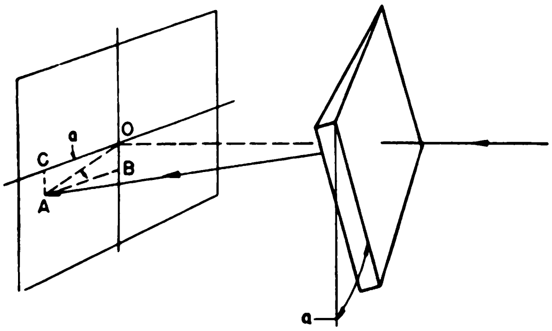
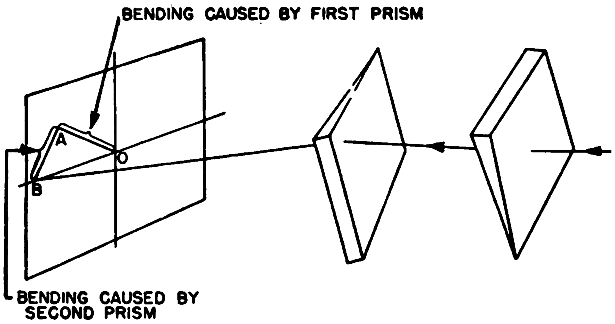


Figure 13-7.—Effect of rotation of the measuring wedge. 55.295

One difficulty remains. The upward and downward bending must be eliminated. This can be done by a second prism, if it is a duplicate of the first prism and is rotated an equal amount in the opposite direction. This will cause both forward and backward and up and down bending, but the up and down bending caused by the two wedges will be in opposite directions and will cancel out. The forward and backward bending of the two wedges will add together, as shown in figure 13-8. On the screen, the first prism causes bending OA, the second AB. The resultant movement is entirely forward and backward and amounts to OB.

Maximum bending to left will be obtained when the two prisms have their thick edges side by side, vertical, and to the left. One of the prisms rotates clockwise and the other counterclockwise, and the amount of bending to the left will decrease until, after 90° rotation, neither prism is causing any fore and aft bending. All of the bending of one prism is up, and the other down, and as the prisms continue to rotate, they will begin to cause bending to the right which will reach a maximum after 180° of rotation.

The amount of rotation of the prisms required to make the target and the ranging mark appear to be at the same distance measures the parallactic angle, thus, it measures the range. If a scale is mounted on one of the prisms to rotate with it, the scale can be graduated in yards of range, and the range can then be read directly.



55.296

Figure 13-8.—Effect of rotating two wedges.

STEREOSCOPIC RANGEFINDER CONSTRUCTION

The structural frame of a rangefinder consists of three long tubes, one inside the other as shown in figure 13-9. The OUTER TUBE is simply a strong airtight cover to protect the optical and mechanical parts. Heavy wrappings of insulating material prevent fluctuations in the temperature of the working parts of the rangefinder. This tube is gastight and is kept filled with helium or nitrogen which prevents the condensation of moisture on the inner surfaces.

The outer tube has a pair of rings around it, one near each end. These rings attach the rangefinder to its mount.

Mounted within the outer tube is the INNER TUBE which is the main structural frame of the instrument. It carries nearly all the optical and mechanical working parts. The only important exception is the eyepiece group which is fastened to the outer tube.

The inner tube is mounted inside the outer tube by means of two bearings. The right-hand bearing is constructed to permit a little movement back and forth along the axis of the rangefinder. Thus, if either of the tubes expands or

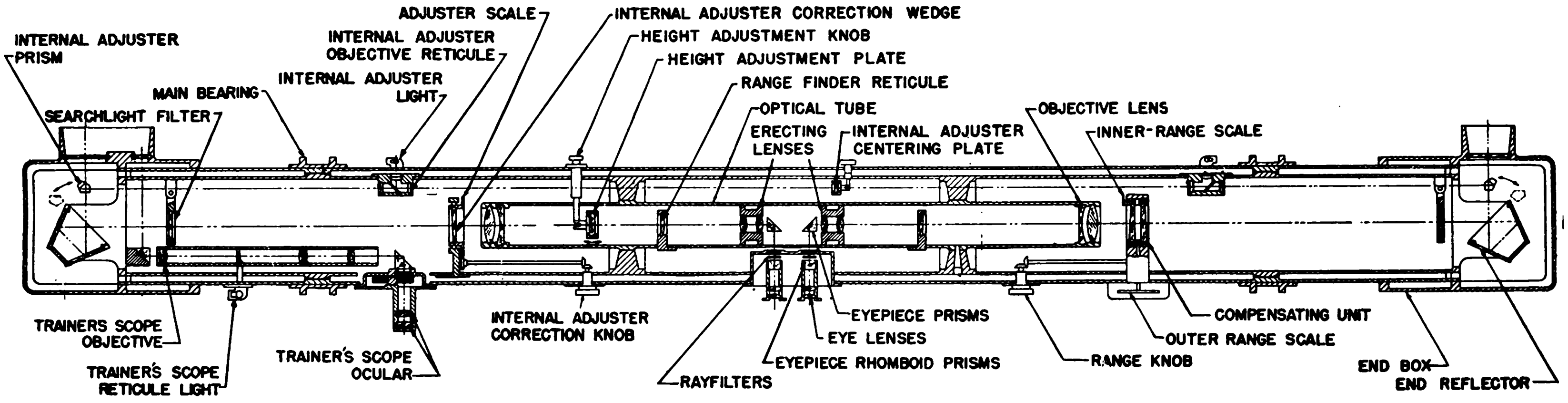


Figure 13-9.—Construction of a stereoscopic rangefinder.

contracts as a result of external stresses or temperature changes, the other tube will not be affected.

Within the inner tube is the OPTICAL TUBE, as shown in figure 13-9. This is a short rigid tube, machined from a steel forging. It contains those optical parts for which rigid alignment is necessary. These parts are the objective lenses, reticules, and the ocular prisms which bend the light toward the eyes. The optical tube is bearing-mounted in the inner tube so that it will not be affected by expansion and contraction.

The penta prisms needed in large rangefinders would be so large that they would be hard to manufacture, so two mirrors, mounted in a box frame, are used instead. The optical effect is the same as that of a penta prism. These assemblies are called END REFLECTORS and are attached by a rigid framework to the ends of the inner tube and protected by an airtight END BOX attached to the outer tube.

Optical glass windows are provided in the end box to admit light to the end reflectors. These windows are part of the optical system of the instrument and MUST NOT be moved. They are slightly wedge shaped so that they bend the entering rays by a very small angle. This bending is used in the last step in the alignment of the instrument at the factory. The end windows are rotated to take out any remaining error and are then cemented in place.

RANGEFINDER ADJUSTMENTS

The first adjustable feature in the rangefinder is in the eyepiece which is focused to adjust the emerging rays to the degree of parallelism or convergence which is most comfortable for the operator's eyes. This adjustment is made separately for each eyepiece by rotating the focusing ring.

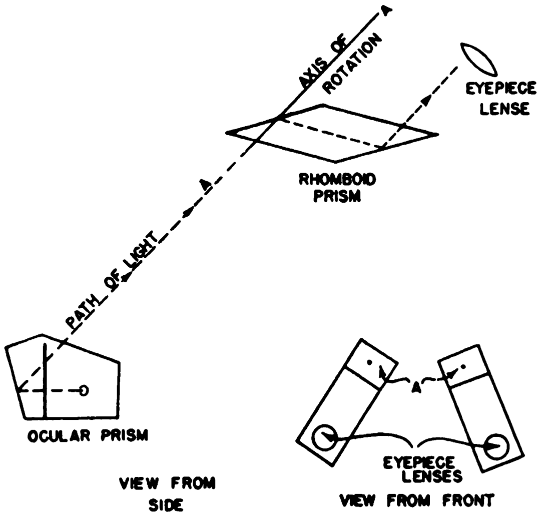
DO NOT close one eye when focusing the other eyepiece. Closing one eye changes the focus of the other. Have someone cover one end window of the rangefinder and then, with both eyes open, focus one of the eyepieces. If you know the proper setting for your own eyes, and know that the focusing scale of the rangefinder is correctly calibrated, you can instantly set the eyepieces to the proper focus for your eyes.

Although it seems obvious, operators sometimes forget that changing the focus will not remedy haze, darkness, or fogged end windows. The operator should determine the diopter setting (which is the adjustment we've been talking about), for his own eyes, on each instrument he uses, under the best possible conditions. He should use that predetermined setting when conditions are unfavorable for accurate focusing.

Interpupillary Adjustment

Figure 13-10 shows how rhomboid prisms in a rangefinder enable you to adjust the spacing of the eyepieces. Since the image is reflected twice in each such prism (as shown), it emerges unchanged in direction. You can see that by pivoting the two rhomboid prisms on the axis A-A (lower right of fig. 13-10), you can adjust the distances between eyepieces. Moving the prisms on this axis does not change the length of the path of light, nor change the orientation of the image in any way.

A small knob or lever, located near the eyepieces, controls this interpupillary adjustment. If you do not know your own interpupillary distance, it might be a good idea to measure it now. Use an accurate interpupillometer and measure to the nearest 1/4 millimeter. Then, whenever you use or inspect a rangefinder, you can set the interpupillary adjustment to the proper value for your eyes.



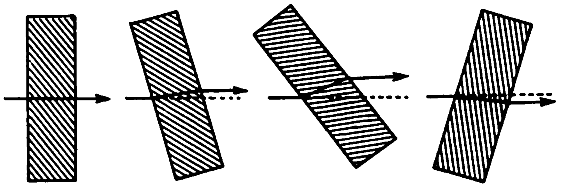
55.298

Figure 13-10.—Interpupillary adjustment.

Height Adjustment

To maintain stereoscopic vision, the images arriving from the two end reflectors must be at the same height. This adjustment is made by tilting a piece of glass, as shown in figure 13-11.

When you refract a ray of light through a plate of glass with parallel sides, the ray is moved to



55.299

Figure 13-11.—Principle of height adjustment.

one side without being changed in direction and the amount it is moved depends upon the angle at which it strikes the plate.

The height adjuster uses this principle. The device is simply a disk of glass, with parallel sides, inserted in the left-hand optical system. The disk is mounted on bearings so that it can be tilted in either direction. Tilting it, as shown in figure 13-11, will raise or lower the image of the target at the focal plane. A knob on the side of the rangefinder controls the tilt of the disk.

One way to make the height adjustment is to aim the rangefinder at some distant target such as the horizon. Set the range knob at minimum range. This should make it possible to break steroscopic vision and to see two separate images of the ranging mark and of the horizon. If one mark appears farther above the horizon than the other, move the height adjustment knob to equalize the distances.

Internal Adjuster Correction Wedge

The rangefinder is a precision instrument built with extreme care, but like any instrument it can get out of adjustment. Many things can cause it to lose its precise alignment. The most common trouble is change in temperature causing expansion and contraction of the various parts. When this happens, the instrument will give incorrect readings, and some means must be provided to compensate for the error. This is the purpose of the internal adjuster correction wedge.

The correction wedge is a thin prism placed in the LEFT OPTICAL system outboard of the optical tube as shown in figure 13-9. Rotation of the correction wedge deviates the line of sight, both vertically and horizontally. The horizontal component of deviation is the most useful; errors in vertical alignment are corrected by adjustment of the height adjuster.

Check the Rangefinder

The correction wedge is used when comparing rangefinder readings with some known distance. Suppose it is known that the distance to some point is 7300 yards. A careful range is taken and the range scale reads only 7000 yards. This 300-yard error must be eliminated.

The next step is to set the range scale at the known range to the target, in this case 7300 yards. Now range on the target WITH THE CORRECTION WEDGE without touching the range knob. When the target and the ranging mark appear to be at the same distance, read the scale attached to the correction wedge known as the adjuster scale. Repeat this operation about ten times, keeping a record of the readings. Finally, set the average value obtained from the ten readings onto the adjuster scale. The instrument should now be in adjustment and ranging with the ranging knob should give correct values at any range. The correction knob is usually covered with a screw cap when not in use to prevent disturbing the setting.

Internal Adjustment

The methods already mentioned can be used for occasional checking of errors in the rangefinder due to variation of weather conditions provided a target is available. Since a target is not always available, some other means of checking the rangefinder must be provided.

The internal adjuster system also provides an artificial target, inside the instrument, which can be used to check the range scale. The placement of the parts of the internal adjuster system is shown in figure 13-9.

Figure 13-12 is a schematic diagram of the entire optical system of a rangefinder. Look at the internal adjuster system at the top figure 13-12. The distance between the two adjuster objective lenses is equal to their focal length. Fastened to each of the lenses is a reticle carrying a target mark, usually consisting of a pair of vertical lines. Each of the target marks is thus located in the focal plane of one of the lenses. Outboard of each lens is a transparent reflector plate.

Consider the left-end reflector. Light from the small internal lamp is reflected from the reflector plate and illuminates the left target mark. Since this mark is in the focal plane of the right objective, rays from the mark will emerge from the right objective parallel to each other. Some will be reflected by the right reflector and be lost, but some will pass through. At the same time the right target mark is illuminated by the right reflector and sends out rays which become parallel after passing through the left objective.

At each end of the adjuster tube is a small penta prism. Ordinarily these prisms are swung out of the way so as not to interfere with the operation of the main optical system. By turning the INTERNAL ADJUSTER DRIVE KNOB you can crank the two penta prisms into position, closing the shutters over the end windows to keep external light out of the system.

If the two objectives of the internal adjuster system are so mounted that their optical axes coincide, then the two sets of rays from the two internal targets will both be parallel to that axis, and after reflection at the two small penta prisms, the two sets of rays will still be parallel to each other. In the stereoscopic rangefinder the operator will see one target with each eye, and the two images will fuse stereoscopically.

The rays from the left and right internal adjustment system are reflected into the main optical system by the adjuster penta prisms. The rangefinder operator will see one target with each eye, and the two images will fuse stereoscopically.

The target will appear at a definite stereoscopic depth or range. So there is one prescribed range at which the scale must be set in order to check its calibration with the internal adjuster system. The operator sets the range scale at this prescribed distance, and then sights through the eyepieces. In the stereoscopic rangefinder the image of the artificial target must appear to be at the same distance as the ranging mark on the reticle; if it does not, the operator must turn the correction knob until it does. The operator repeats this operation at least five times and sets the median correction on the range scale.

On the stereoscopic rangefinder, the internal adjustment is easier to make if the ranging mark on the reticle is centered between the two vertical lines of the artificial target. If it is not, turn the internal target adjuster knob (also called the collimator knob) to center it. The artificial target should never appear to touch the ranging mark; if it does it will interfere with your stereoscopic judgement.

Scales

Two range scales are provided on modern rangefinders, an external scale and internal scale. These scales are shown in both figures 13-9 and 13-12. The internal scale is a ring scale directly attached to the ranging wedge of the instrument and turning with it. Its position is always an accurate indication of the actual setting of the ranging wedge.

The internal range scale is read by means of an auxiliary reading telescope built into the rangefinder. Figure 13-12 shows that the reading telescope consists of an arrangement of lights and prisms to illuminate the scale, an objective lens, a collective or field lens, and an eye lens.

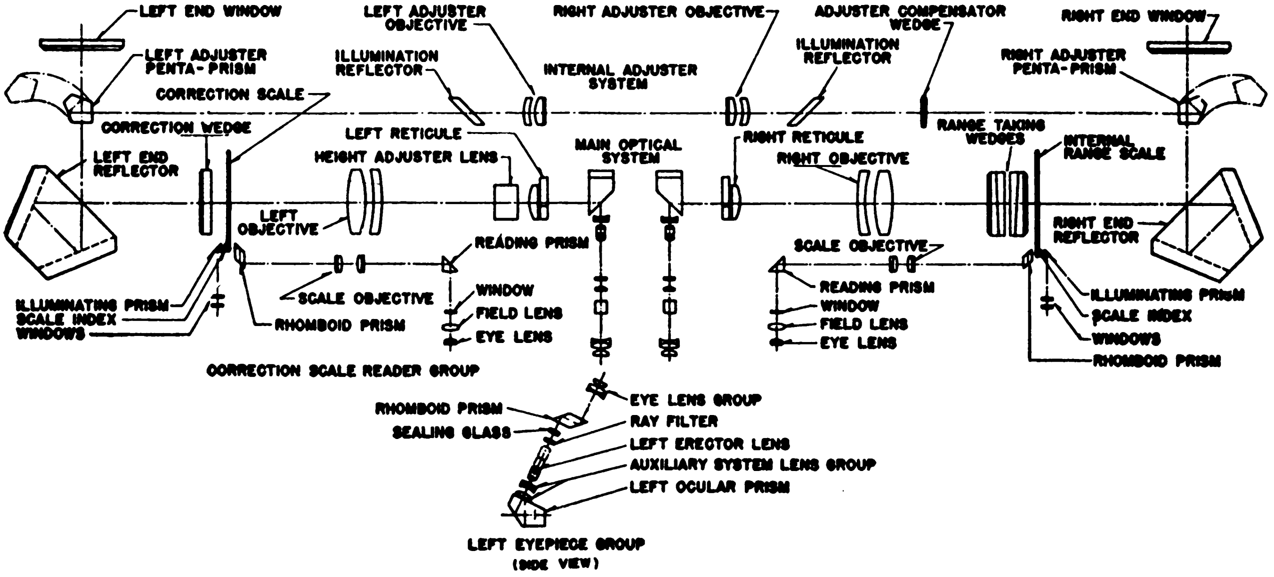


Figure 13-12.—Optics of the rangefinder.

55.300

The window shown in the illuminating system is to protect the airtight seal of the instrument.

The external scale is a second dial placed near the outside of the rangefinder so that it can be read through a window without the aid of artificial light, if the illuminating circuit for the internal scale should fail.

An occasional check should be made to see that the two scales are giving the same reading. If a discrepancy is found, it may indicate excessive lost motion or that the adjustment coupling between the external scale and the wedge is out of adjustment. In either case, repairs should be made by an Optical Repairman.

The internal adjuster correction wedge is read by means of an internal adjuster scale only, and has an optical system similar to that of the internal range scale. The adjuster scale is calibrated in UNITS OF ERROR.

RANGEFINDER ACCURACY

Range measurement with the stereoscopic rangefinder is based on the ability of the operator to see whether the target and the ranging mark appear to be at the same distance. That is, accurate measurement depends upon the ability of the operator's eyes to detect whether the rays coming through the eyepiece from the target are parallel to the rays from the ranging mark.

The smallest difference of parallactic angle which the eye can detect is approximately 12 seconds. This means that when the rays from the target and from the ranging mark appear to be parallel, they may actually make an angle of nearly 12 seconds with each other. Thus, when the rangefinder scale reads 10,540 yards, the actual distance to the target may be greater or less than 10,540 yards. The error may be any amount which does not change the parallactic angle observed by more than 12 seconds.

This distance by which the scale value of range is uncertain is called the UNIT OF ERROR. It is the distance in yards by which the range will change if the parallatic angle at the eye changes 12 seconds.

You can readily see that the value of the unit of error will become smaller as the base length and magnification of the instrument are increased; and figure 13-13 shows you that the value of the unit of error will be different at different ranges—the greater the range, the greater the unit of error.

It is easy to figure out the exact value of the unit of error from the formula:

$$e = \frac{58.2 R^2}{BM\ 1,000^2}$$

or,

$$e = \frac{58.2}{BM}\left(\frac{R}{1000}\right)^2$$

In this formula, e is the range error in yards due to one unit of error:

B is base length of the rangefinder in yards;
M is the magnification of the rangefinder;
R is the range in yards;
58.2 is a constant valid only when the operator stereoacuity is 12 seconds.

The formula proves that the unit of error becomes less as base length and magnification of the instrument increase. In short, large rangefinders are more accurate than small ones. It also shows that the size of the unit of error in yards increases as the square of the range. This means that you can expect four times the error when you double the range. Table 13-1 tabulates the values of the unit of error at different ranges for a 15-foot rangefinder with 24X magnification.

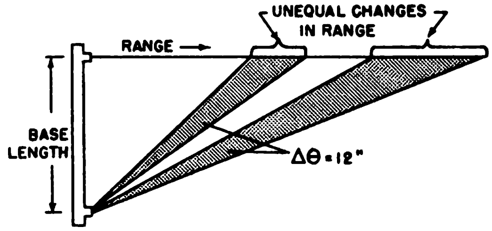


Figure 13-13.—How the unit of error increases with range.

55. 01

Table 13-1.—Values of Unit of Error for a Typical Rangefinder.

Range Yards	U. of E. Yards	Range Yards	U. of E. Yards
1,200	0.7	14,000	95.0
1,500	1.1	16,000	124.1
2,000	1.9	18,000	157.1
2,500	3.0	20,000	193.9
3,000	4.4	25,000	303.0
4,000	7.8	30,000	436.0
5,000	12.12	35,000	594.0
6,000	17.5	40,000	776.0
8,000	31.0	45,000	982.0
10,000	48.5	50,000	1,212.0
12,000	69.8	-----	------

A-Curve

The A-curve shows the value in yards that a change of one unit of the adjuster scale will produce at various ranges. At least three objects X, Y, and Z, at different ranges are selected to get the readings necessary to plot this curve.

The operator takes an accurate internal adjustment check. Ten ranges are taken on object X and recorded. The adjuster scale is then deliberately set 10 units high and ten more ranges are taken and recorded. The same is repeated for a setting 10 units low. The internal adjuster scale has been offset a total of 20 units (+ 10 and -10). When the range difference obtained with these settings is found, the difference which has resulted from a change of 20 units can be divided by 20 to find the change produced by one unit. The same procedure is repeated for objects Y and Z.

The change in reading in yards that one unit of the adjuster scale will produce for targets X, Y, and Z is plotted against the rangefinder range to X, Y, and Z. From the curve drawn through these points the value in yards of one unit of the internal adjuster scale at any range can be determined as shown in figure 13-14.

Once the A-curve is constructed, if the rangefinder error at a given range is known, it is possible to determine the number of units the internal adjuster scale must be moved to correct for this range error, since the curve gives the change in yards which a change of one unit of the adjuster scale will produce at any range. To make this information readily available for any range, a B-curve, utilizing the data of the A-curve, is prepared. The B-curve is shown in figure 13-15.

B-Curve

To construct a B-curve, rangefinder ranges are taken on targets at various ranges where the range of each target is accurately known. The difference between the measured rangefinder range and the actual range of the target is the range error. Knowing (1) the error in yards, and (2) the value in yards on one unit of adjuster scale from the A-curve, the number of correction units required to make the rangefinder read true range is obtained by dividing (1) by (2). The resultant value plotted against

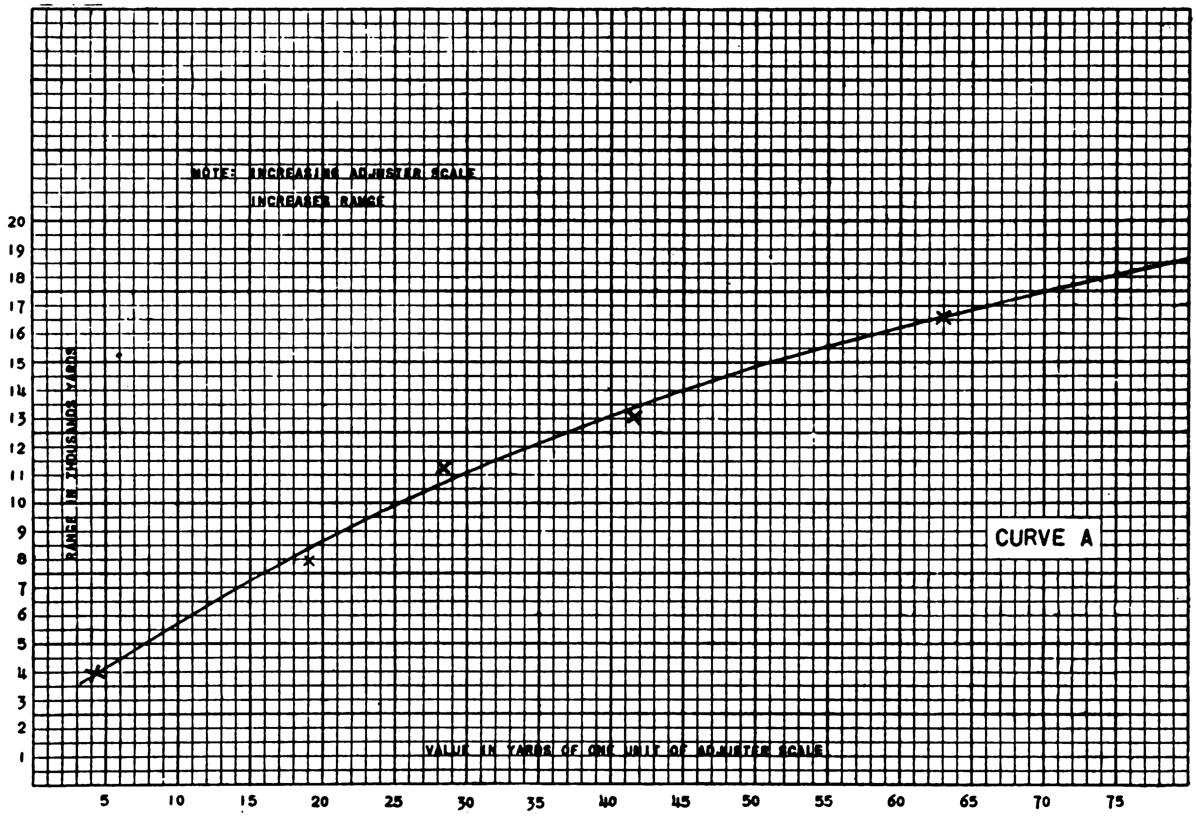


Figure 13-14.—Typical A-curve.

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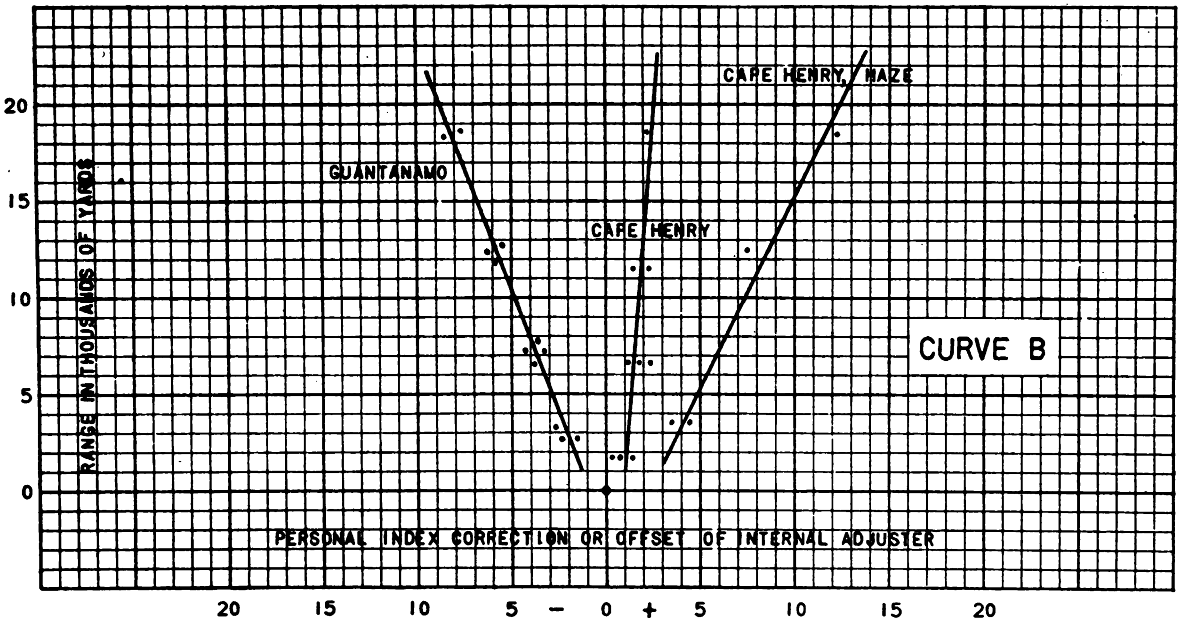

RANGEFINDER NO. 2 OBSERVER'S NAME Fred Smith FT2

CONDITIONS OF OBSERVATION			
LOCATION	GUANTANAMO	CAPE HENRY	CAPE HENRY
TIME OF YEAR	JAN. TO MARCH	JAN. TO JAN.	OCTOBER
WEATHER	GOOD, CLEAR	FAIR	HAZE
TEMPERATURE	87 TO 96	VARIOUS	69 TO 75
ETC.			

Figure 13-15.—Typical B-curve. 55.333

the rangefinder range of the target gives a point on the curve. Several such points are plotted for each B-curve. For accurate results, widely spread ranges are taken on at least three different targets, under various conditions, as shown in the example of figure 13-15. A series of at least 10 ranges is taken on each target and the readings are recorded and averaged.

The B-curve of figure 13-15 is for one rangefinder operator. It is evident that internal corrections will be different (1) in the same locality under different weather conditions, (2) in different localities, and (3) for each different rangefinder operator. The B-curve shows corrections for Guantanamo and for Cape Henry under normal and hazy conditions. Let's assume that a practice is to be fired in the Cape Henry area under hazy conditions at 15,000 yards. It can be seen that + 10 units is the index correction. This means that 10 units should be added to this operator's internal adjustment setting, since the index correction taken from the B-curve should always be applied to the internal adjuster scale setting after the internal adjustment has been made.

In all calibrations the most important consideration is the accurate range to the target. In many localities special rangefinder calibration charts are provided with suitable targets at various ranges clearly identified. However, there is still the problem of obtaining an accurate position on the charts for own ship. This is done by standard navigational methods. It is to be noted that the anchorage bearings from ship's logs are not sufficiently accurate due to swinging of the ship; also, it must be remembered that if the rangefinder is located at some distance from the bridge, allowance must be made. Radar offers an excellent means for determining correct range to check against; radar range eliminates the need for checking the position of the ship.

SPOTTING WITH THE RANGEFINDER

The long base rangefinder is an ideal spotting instrument because you can tell clearly whether the fall of shots is short or over. But to do intelligent spotting it is essential that you understand the unit of error. Here is how it works. In addition to the ranging mark, the reticles of a rangefinder contain several other marks. Figure 13-16 shows a typical arrangement of one of the reticles.

The large diamond in the center is the ranging mark. This large mark is located on the optical axis. The small diamonds are spaced the same distance from the axis on both reticles, thus rays coming from the corresponding diamonds on the two reticles are parallel to each other, and the small diamonds appear to be at the same distance as the ranging mark. The diamonds are spaced so that the angle between them at the eye is five mils. They can therefore be used for spotting a splash in deflection.

All the marks in any one horizontal row appear to be at the same distance, but the various rows appear to be at various distances. To the operator, the upper rows appear to be more distant than the diamonds; the lower rows appear closer than the diamonds. The marks in the first rows above and below the diamonds are so spaced that their apparent distance from the diamonds is equal to 50 units of error. The second rows from the diamonds appear to have a range difference of 100 units of error.

In ranging, the operator rotates the measuring wedge until the diamonds and the target appear to be at the same distance. He need not change this setting to measure the distance from the target of a burst or splash. By using the vertical marks for reference, the operator can estimate the spot in units of error, which can then be converted to the equivalent in yards for that particular range.

CARE OF THE RANGEFINDER

Rangefinders require careful handling and operation to produce satisfactory results. Only regular rangefinder personnel should operate them. The rangefinder is hermetically sealed, and is filled with an inert gas under pressure. Under no circumstances should an FT break the gas seal. Repairs affecting the internal optical systems of a rangefinder should be accomplished only by qualified optical repair personnel.

In cleaning the external optical surfaces, dirt or grit should be removed with a camel's hair brush to avoid scratching the surface. Then use clean lens paper or chamois for wiping the optical parts. Cleaning lenses with alcohol or ether should be restricted to experienced repair personnel, as both substances will dissolve the balsam used in cementing the lenses.

External mechanical moving parts should be lubricated periodically in accordance with a prescribed program. Care should be exercised, as oil or oil vapor must never reach the lenses.

The rangefinder should be protected from the weather and spray when possible. The optics should not be exposed to the direct rays of the sun unless necessary during operation. End windows and operating knobs should always be protected by their covers when the instrument is not in use.

A periodic inspection of the rangefinder, looking through both ends of the optical systems, should be made by the FT. He should be on the lookout for silver plating peeling from the mirror surfaces, dust and dirt, moisture fogging, and pitted or discolored lenses. The rangefinder and other gas-filled optics should be regassed periodically. This should be an item in your ship's CSMP.

The tendency to neglect calibration of rangefinders and training of rangefinder operators, and to place full reliance on radar for ranging, should be avoided. Radar offers an excellent means of determining correct range. But there are conditions under which radar cannot measure range. For example, a target located ashore may be masked to the electronic eye but not to the human eye. Well-calibrated rangefinders with efficient operators then become the primary method of measuring range, and they must be ready for instant use.

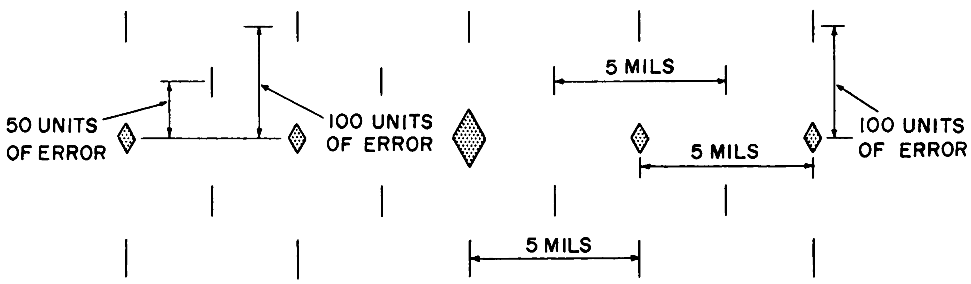

Figure 13-16.—Typical reticle pattern.

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CHAPTER 14

GENERAL MAINTENANCE

Since you became an FT 3, your duties have become more technical. Because of your increased experience, more is expected of you. New responsibilities go with increased knowledge and skill. Part of your responsibility is to perform or supervise the operation, test, and maintenance of the equipment in your battery. This chapter will help you in general maintenance and troubleshooting techniques.

ADVERSE CONDITIONS

Because the fleet is an operating fleet, your equipment is subjected to extreme temperatures, high humidity, salt, and dust. High temperatures and moisture cause rapid deterioration and corrosion. Salt, when moisture is present, will deteriorate metals, and is a conductor of electricity. Dust is a cause of fungus spread. Fungus growth causes decay, rapid deterioration of insulating materials, and shorts or grounds in electrical circuits. We will cover in general terms our defense against these troublemakers.

MOISTURE

The battle against moisture is never-ending. Moisture creeps into the smallest openings. Watertight covers must be kept watertight. When you remove a cover, check the condition of the gasket, the knife edge, and the securing bolts or dogs. Where possible, when checking an electrical circuit, use a connection box in a protected space. When moisture is discovered in an instrument or connection box, dry it out with a hot air blower or an electric lamp.

A reasonable degree of protections against the accumulation of moisture is obtained by a daily energizing and workout of the equipment.

Variations in temperature cause air to be breathed through any opening or vent in the equipment. As the temperature rises, the air inside a piece of equipment expands and is partly expelled. When the temperature falls, the air inside the equipment contracts and outside air is admitted. As the air cools, condensation or sweating takes place. Electrical heaters are installed in some instruments to eliminate this source of moisture. The heater keeps the interior of the instrument at a temperature higher than that of the surrounding air. In many instruments, the circuit to the heater bypasses the power switch, and voltage may be present even though the power switch is off. Remember this when working around the heater circuit.

SALT AND FUNGUS

Salt or fungus found in your equipment should be removed immediately. Under some circumstances you can use fresh water to remove them. After cleaning the equipment, however, make sure the water is completely evaporated. A cleaning solvent, methyl chloroform, can be used to clean away salt or fungus. But methyl chloroform will attack electrical insulating materials and contact time should be limited. High concentration of methyl chloroform vapor can be dangerous to life. Adequate ventilation is necessary when it is used.

DUST

Most mechanical equipment is enclosed in a dustproof housing. If you use reasonable precautions, the dust problem in this equipment is small. Before you remove a cover, be sure the surrounding area is clean and that all likely sources of dust have been eliminated. A major source of dust is the ventilation system. When working on precision equipment such as a computer, the ventilation system should be secured. If you cannot secure it, cover the blower duct openings with cheesecloth or gauze.

Most electronic equipment has a serious dust problem. This is a direct result of the heat problem. Heat is dissipated by air taken into the unit and circulated. Air filters are installed, but they are not 100 percent effective. The housing is not dustproof, so you can expect to find some dust in electronic units.

You should clean electronic units frequently. To clean an electronic assembly, use a soft brush and a vacuum cleaner with a nonmetallic hose. Keep in mind that even though the power is off, dangerous potentials may still be present.

EQUIPMENT TEMPERATURE

A high ambient temperature can cause equipment failure or malfunction. Ambient temperature is the temperature of the immediate area surrounding a component or unit. The characteristics of electrical circuits change with a change in temperature. When the ambient temperature is high, or when the equipment produces enough heat to raise the ambient temperature significantly, the equipment must be artificially cooled. Forced air is usually used for this purpose, with filters to remove the dust and other foreign material from the airstream. But dust tends to clog the filters, and reduce the airflow. To prevent this, you will have to clean the filters frequently.

When you are testing or servicing air-cooled equipment, do not operate it for long periods with the doors open or the covers removed. This would allow the cooling air to escape before passing through the equipment.

Compartments containing equipment that produces a lot of heat are given special consideration when the ship's ventilation system is installed. Be sure the ventilation system is working efficiently in these compartments. Do not store any gear which would hinder the dissipation of heat around operating equipment.

Tube failures are often caused by the mechanical breakdown of one of the tube elements. The tube elements expand as the filament is heated, and contract when the filament cools off. When the tubes in a unit are initially energized, a surge of current passes through the filaments. These factors may ultimately cause a tube failure. Therefore, when electronic equipment is to be operated intermittently, it is better to leave the filaments energized.

LUBRICATION

Proper lubrication helps eliminate the heat problem in mechanical equipment. Lubricants are used to reduce friction, dissipate heat, and prevent corrosion. All moving parts cause friction, which generates heat and causes wear. Contacting surfaces are subject to seizing. To reduce friction and prevent seizing, interfacing surfaces are separated by an oil or grease film. The lubrication procedure is not complicated, but strict adherence to it is necessary. An overlooked lubrication point may easily lead to equipment failure. The fact that an overlooked lubrication point cannot always be detected makes it all the more important to pay attention to details.

Lubrication instructions are issued for all ordnance equipment. Most of these instructions are in the form of charts in the equipment's OP. OD 3000 gives general lubrication instructions for ordnance equipment.

Lubrication charts indicate the type and amount of lubricants, lubrication points, and frequency of application. In addition, the charts may contain other maintenance functions to be performed in conjunction with lubrication. Don't trust your memory. Use these charts and a checkoff list with a systematic schedule.

Do not overlubricate your equipment. Excessive lubricant acts as an insulating blanket and prevents the dissipation of heat. Overfilling or overheating may cause overflow into adjacent electrical equipment. Lubricants generally deteriorate electrical insulation materials.

Cleanliness is important in lubrication. Dirt in a lubricant makes a damaging abrasive material. Plastic protective caps are used on grease fittings.

REPAIR AND OVERHAUL OF FIRE CONTROL INSTRUMENTS

Reliability is designed into fire control equipment. With proper care, the equipment will give long years of service. Each instrument undergoes a series of tests before the Navy will accept it. It is installed by experts; and before the ship will accept the equipment, it must work at designed efficiency. It is your job to maintain this peak performance of your equipment.

The attitude you assume toward your equipment will govern your maintenance behavior. This equipment deserves your respect. Think of the job your fire control system does, and often under adverse conditions. The equipment often must be of intricate and delicate design and have a high degree of accuracy.

The first requirement in any maintenance program is to know your equipment. This knowledge can be obtained from the OPs on the equipment, tests and checks held during preventive maintenance, and operation of the equipment. When your equipment is working correctly, study its performance in all modes of operation. A firm grasp of the fundamentals is essential. This knowledge can be obtained from your Navy Training Courses.

The majority of casualties can be corrected by minor repairs. Quite frequently the hardest part of the repair job is to find the fault. Before going into an instrument, check its operation in all modes of control. Run all likely tests. Take full advantage of the test features designed into the equipment. If there is an alternate supply, or if an input can be received from a different source, try them. In Fire Control Technician 3, NavPers 10173-A, a troubleshooting procedure is described. The procedure will reduce the time required to find the source of trouble.

Before beginning the actual repair, be sure of your facts. Take your time and think; don't jump to conclusions. Resist the temptation to learn more about the casualty by prematurely disassembling or adjusting the instrument. An instrument loses some of its precision each time it is desassembled. Adjustments are provided to compensate for changes in the values of associated components. This is normally due to wear, age, or environment. Adjustments are not there to correct casualties. Don't make an adjustment unless you are sure it is the correct step.

A fire control instrument may have a component that fails periodically. You can find out about such components by reviewing the machinery history cards and log books. Some electronic circuits are critical, and not all tubes of the right type will work. This normally will be noted in the equipment OP, or Fire Control Maintenance Notes, OD 9398.

Remember, the equipment worked before the casualty occurred. Therefore, a change to the original wiring or installation will not help you. Check your test equipment before you use it.

Frequently the easiest way to check a suspected component is by substitution. Do not make wholesale substitutions, for you just might increase your trouble. Before you replace a component, make sure the replacement is good, and is identical with the original component.

When you find that a defective component has caused the casualty, check the circuits to and from the component. The component may have broken down due to normal usage; but another casualty may be present which caused the breakdown, or was caused by it.

Only after you have completely exhausted all other possibilities and have a good idea of where and what the trouble may be should you disassemble a piece of equipment. It is embarrassing, to say the least, to be in the middle of disassembling an instrument and find that the trouble is a blown fuse.

Follow step by step the disassembly and reassembly procedures in the OP. Don't take shortcuts, and don't get ahead of yourself. This is a natural tendency when you are familiar with the instrument and become overconfident. Review the procedure at each step, and study the next step carefully.

Don't leave hardware (nuts, bolts, screws, washers, spacers, and the like) adrift. Each piece of hardware has a particular job to do; without it, the job is not done.

Safety features are built into the equipment for your protection. Don't bypass them. But if you must, be sure of your grounds. The word grounds is a double-entendre. In some electronic equipment the chassis is grounded to the cabinet. When removed from the cabinet and placed on an insulation material, the ground is lost. In this case, much to your discomfort, you might furnish the ground connection.

TROUBLESHOOTING TECHNIQUES IN ELECTRONIC EQUIPMENT

We will assume the trouble has been localized into an electronic assembly. An electronic assembly has stages, which make natural divisions for troubleshooting. The stages are named for the function they perform. We can group the stages used here into the following categories—(1) power supply, (2) amplifier, (3) connecting circuit, (4) receiver circuit, and (5) output circuit.

SIGNAL TRACING

Signal tracing means testing the input and output of each stage. In a faulty amplifier, the signal would appear at the input, but not at the output; it would stop at the defective stage.

Two instruments can be used to test the input and output—the a-c vacuum tube voltmeter (VTVM) and the cathode-ray oscilloscope (CRO). Either instrument is connected between cathode and grid to test the input, and between cathode and plate to test the output.

The VTVM measures the amount of voltage at the input and output. You compare these two voltage readings to check the voltage gain of the stage.

NOTE: A high resistance voltmeter must be used for checking plate voltage so that the current drawn by the meter is negligible when compared to the tube plate current.

When signal tracing, a blocking capacitor (either internal or in one of the VTVM leads) is used to keep the direct current out of your reading.

The CRO also measures the amount of the input and output voltages—it also checks the voltage gain of the stage. In addition, the CRO shows the sine wave form. And from the sine wave form you can measure distortion.

Mk 6 Stable Element Preamplifier

Use the Mk 6 stable element preamplifier circuit in an exercise of signal tracing. This will show you how to test the inputs and outputs of each stage.

Look at figure 14-1—this is the circuit to be tested. Notice the numbers at each electrode in the 6A6 tube. These numbers represent the base pins or socket terminals of the tube. The base pins are often called the SIGN POSTS of troubleshooting—they're the points where you connect the VTVM or CRO.

First, apply a signal to the input circuit. There are two ways to do this. You can use the 60-cycle TEST SIGNAL from the CRO, or you can displace the pickup device—in this case, the umbrella coil. Either method puts a signal across the primary of T1.

Next, test the final output of the preamplifier. Connect a VTVM or a CRO across the primary of T2. Either an incorrect voltage reading or a distorted wave form indicates trouble in the preamplifier.

It's usually easier to test the output by connecting the meter between pins 4 and 6. The voltage between pins 4 and 6 is the output voltage because this is the voltage across the T2 primary.

Next, test for a signal input between pins 3 and 4. If you get no signal or a distorted signal, the trouble is in the input circuit. You'd test the components in the input circuit.

If you get a normal signal input between pins 3 and 4, the trouble is farther along in the amplifier. You'd go on to test the output of the first stage—between pins 2 and 4.

If you get NO signal or a DISTORTED signal between pins 2 and 4, the trouble is in the first stage.

Assume that the trouble is in the first stage. A voltmeter across R24 will indicate whether the bias voltage is normal. If it is zero, check the plate voltage to cathode and to ground. A high plate voltage to ground and none to cathode indicates that R24 is open. Equal voltages from plate to cathode and plate to ground indicate that R24 is short-circuited or the tube plate, cathode,

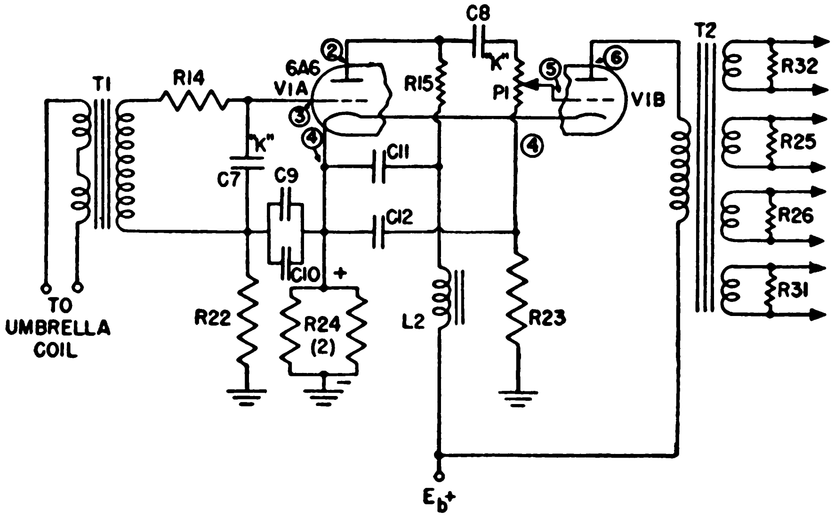

Figure 98.—Mk. 6 stable element, pre-amplifier.

Figure 14-1.—Mk 6 stable element preamplifier.

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or heater circuit is open within the tube or socket. If the bias is high, check R15 for a short and check the tube. A low plate voltage indicates that R15 may have increased in resistance, C8 or C11 may be shorted or the tube may be gassy.

If the d-c voltages are normal but the signal from 2 to 4 is of reduced amplitude, C11 may be open or L2 shorted.

If the signal from 2 to 4 is normal, proceed to test the second stage in a similar manner.

Signal Tracing With The CRO

Signal tracing with the CRO is the most accurate method of testing. The CRO pattern gives you the EFFECT produced by a casualty. Knowing the effect, you can reason out the CAUSES which may produce the effect.

Many times you'll find the different casualties produce the same CRO pattern. But, CRO signal tracing narrows down the possible casualties—there are only a few casualties in each stage that can produce the same CRO pattern.

We will use the CRO to trace a signal through the basic amplifier in figure 14-2. First, apply a signal to the input circuit. There are two ways to do this. Either use the pickup device to originate the signal—in this case you would use the control transformer; or use an external signal source—in this case you would use the 60-cycle test voltage from the CRO.

Next, connect the CRO for signal tracing. The CRO ground lead is connected to any point marked G in figure 14-2.

Now, you're ready to trace the signal. First, measure the input. Connect the vertical input lead to test point 1. Then adjust the CRO until one or two cycles appear on the screen. You'll get a better wave pattern if you leave the synchronizing voltage at zero. As you know, this allows the pattern to creep across the screen. By adjusting the fine frequency control, you can slow it down until the pattern is easy to read.

The pattern at test point 1 is the signal input. You can use the size of this pattern as a reference to check the voltage gain—remember where the CRO controls are set.

Move the vertical lead to test point 2. This tests the input to the first grid. You should get a smaller wave than the signal wave because of the voltage losses across P1 and P2. You may have to readjust the CRO vertical gain to get a good wave pattern of this smaller voltage.

No signal at test point 2 means an open P1, R1, P2, or a shorted C1. A shorted C1 would probably cause P1 to overheat and burn out.

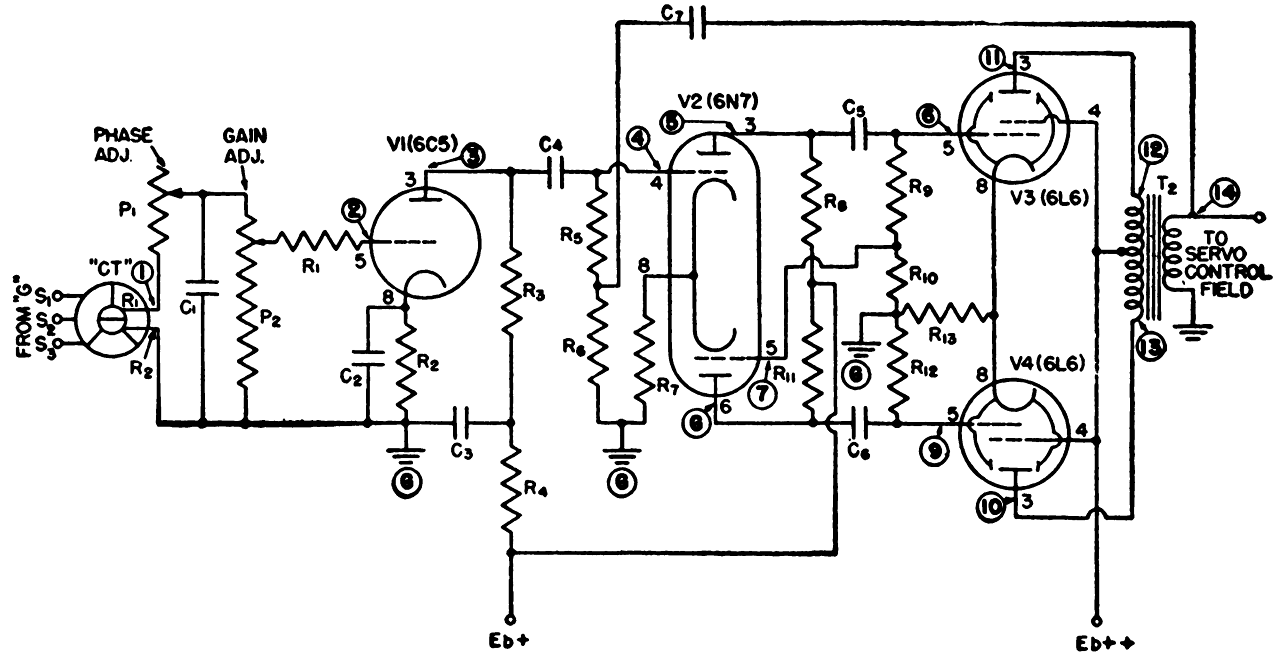

Figure 14-2.—Basic amplifier.

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If the pattern from test point 2 is flat or has a dip at the top or bottom, grid current is responsible.

NOTE: Too large a signal at the oscilloscope input may cause a distorted curve. Whenever the oscilloscope shows a "flattened" signal, reduce the vertical gain and notice whether the distortion disappears. If it does, then the distortion is being produced in the oscilloscope and the amplifier being tested is not at fault.

There are three casualties that can cause grid current here and produce this kind of distorted pattern. First, too large a signal drives the grid positive on the positive signal peaks. Second, insufficient bias at R2 allows the signal to drive the grid positive. Third, a gassy 6C5 causes grid current.

If the tube is not gassy, it is not producing the distortion, so you reduce the signal at P2 or at the control transformer. Reducing the signal will fill out the pattern IF the distortion is caused by too large a signal. If a reduced signal does not fill out the pattern, bias failure is probably the casualty.

Move the V prod to test point 3. You should get a sine wave that is 10 to 20 times larger than the wave at point 2. The larger wave is due to the voltage gain of V1. Also, the pattern at point 3 should be as distortion free as the pattern at point 2. No distortion should be produced between points 2 and 3, since V1 operates as a class-A amplifier.

No signal at test point 3 means a short or an open component in the cathode-plate circuit or a faulty tube or lost plate supply Eb+.

Distortion at test point 3 could mean too large a signal. Try to remove the distortion by reducing the signal at P2 or at the control transformer.

A flattened wave form at test point 3 may mean a reduced Eb+ voltage or a leaky C3. A leaky C3 shunts V1 and R3—changing the Ep on V1.

Move the V prod to test point 4. You should get an undistorted wave with less amplitude than the wave at point 3. This signal reduction is due to the negative feedback across R6.

If the pattern at point 4 is reduced too much, C7 is probably shorted, or R6 may have increased in value.

If the pattern at point 4 is not reduced at all, look for an open at C7, a shorted R6, or for a failure somewhere farther along in the amplifier. For example, an open C5 would mean zero signal to the 6L6 tubes, and zero feedback—the signal at point 4 would not be reduced, because there is no feedback.

Here's a quick way to check the feedback voltage. First, measure the V1 OUTPUT VOLTAGE across R5—you can consider the R5 voltage to be the V1 output, because R6 is very small compared to R5. Next, measure the feedback voltage across R6. Then compare the V1 output to the feedback—the feedback voltage should be smaller than, and 180° out of phase with, the V1 output. Also the voltage between test point 4 and G should be the difference between the V1 output and the feedback.

Remember—when you measure the voltage across R5, reconnect the CRO ground lead so as NOT to include R6.

Here's a tricky one. Say that you get a perfectly undistorted output at point 3, but distortion appears at point 4. This means the distortion is occurring beyond point 4.

Here's how that distortion might be produced. A leaky C5 would distort the output at T2. Result—a distorted feedback combines with an undistorted signal in R6. The distorted feedback produces the distortion at point 4.

As you found at point 3, a shorted or leaky C4; causes a positive bias on the first grid of V2. This positive bias shows up as a greatly reduced and distorted signal at point 4.

But something else can cause abnormal current through R5 and R6—a gassy 6N7. Move the test prod to test point 5. You should get an undistorted wave 15 to 20 times larger than the wave at point 4. No signal at point 5 may be caused by a number of casualties. A bad 6N7, a plate supply failure, an open R8, or a ground in the plate circuit will all show up as no signal at point 5.

A small distorted wave at point 5 can be caused by a leaky or shorted C4 or C5.

Move the test prod to test point 6. You should get an undistorted wave exactly the same size as the wave at point 5. No signal at point 6 means an open C5 or a grounded grid in V3.

A small distorted signal at point 6 may be caused by a shorted or leaky C5 or by a gassy V3.

If either R9 or R10 is open, the V3 grid will lose its d-c grid return circuit. The floating grid which results causes intermittent blocking and erratic operation. This will show up as a distorted and erratic CRO pattern.

A shorted R13 removes the 6L6 biases. You'd expect this loss of bias to cause large distortions.

For small signals, the negative feedback through C7 will offset the bias loss, and the distortion will not show up. However for LARGE signals, a shorted R13 produces a definitely distorted pattern at point 6. However, a shorted R13 will cause excessive plate current. T2 would overheat.

Move the test prod to test point 7. You should get an undistorted wave exactly the same size as the wave at point 4. But the point 7 wave should be exactly 180° out of phase with the point 4 wave.

No signal at point 7 means either a grounded grid, a shorted R10, or an open C5 or R9.

An overlarge and distorted signal at point 7 is caused by an open R10. The open R10 causes a floating grid in V3 and at pin 5 of V2.

Move the test prod to test point 8. You should get an undistorted wave which is 15 to 20 times as large as the wave at point 7. This wave should be exactly as large as the wave at point 5. But it should be 180° out of phase with the the wave at point 5. Remember—the 6N7 is the phase inverter for the 6L6 push-pull stage.

No signal at point 8 usually means a failure somewhere before point 5. However, a shorted or open R11 would also show up as no signal at point 8, as would an open cathode, grid, or plate element connection or a grounded grid.

A leaky or shorted C6 causes grid current in V4. This will show up as a distorted signal at point 8.

Move the test prod to test point 9. You should get an undistorted wave exactly the same size as the wave at point 8.

No signal at point 9 means either an open C6, a shorted R12, or a grounded grid in V4.

A distorted signal at point 9 means grid current in V4. This grid current can be caused by either a shorted C6 or a gassy V4.

A shorted R13 will also cause distortion at point 9 as at point 6.

An open R12 will cause an intermittent output, from V4 as an open R9 did for V3.

Move the test prod to test point 10. You should get an undistorted wave about 10 times as large as the wave at point 9.

No signal at point 10 means either an open C5, an open R13, and open center top on T2, or a broken Eb++ lead.

You might expect NO SIGNAL at point 10 for an open C6, a grid-cathode short in V4, or a shorted R12. Actually, you'll get a SIGNAL that is only slightly reduced. Here's why—the Ip of V3 set up a swinging current through half of the transformer primary and this induces an a-c voltage in the other half of the transformer primary. Another contributing factor for the signal at point 10 is the common cathode resistor R13.

A greatly reduced signal at point 10 or 11 may be caused by a failure in screen grid voltage supply. If the signal at point 10 is reduced AND distorted, probably some of the turns in T2 are shorted. Shorted turns in T2 increase the plate current of the 6L6 tubes and hence the plate losses.

Move the test prod to test point 11. You should get an undistorted wave about 10 times as large as the wave at points 5, 6, or 9. No signal at point 11 means either an open C5, a grounded grid in V3, a shorted R9-R10, an open R13, or a broken Eb++ lead, a plate cathode short in V3 or an open grid, plate, or cathode lead in V3 or its socket.

Shorts in the T2 secondary or servocontrol field increase the plate current and plate losses in the 6L6 push-pull stage. This distorts and REDUCES the output.

Opens in the T2 secondary or servocontrol field unload the 6L6 push-pull stage. Result—the 6L6 output may distort and usually will INCREASE in voltage amplitude.

That's the end of CRO signal tracing—you've seen the patterns for most possible casualties in the amplifier of figure 14-2. But you've also seen that the same pattern can indicate more than one casualty. In other words, there are a number of probable casualties for each CRO pattern.

The next step is to pick out the ACTUAL casualty from among the probable casualties.

PINPOINTING BY VOLTAGE TESTS

CRO tests localize a casualty at one stage or in one section. But VOLTAGE tests pinpoint the casualty at the one defective part.

Voltage tests measure the d-c electrode voltages. Then the measured voltages are compared to STANDARD electrode voltages. Differences between the measured voltage and the standard voltage indicate a casualty.

The OPs and ODs give you the test points, the meter specifications, the standard voltage reading, and the probable casualties for off-standard readings. You'll find all this information arranged in test charts—a separate test chart for each piece of gear.

The voltage test charts are good—and they're accurate. But to make all the voltage tests takes a lot of time. You'll locate a casualty much faster by first localizing the trouble at one stage, and then using the voltage tests to pinpoint the casualty.

There are two things to remember whenever you make voltage tests. First, allow a resonable difference between the measured voltage and the standard voltage. This reasonable difference must be allowed to offset any meter error or any error due to the tolerance of the parts being tested. Second, follow the meter specifications in the test chart. Always use a meter with the specified sensitivity rating. And use the meter scale specified in the test chart.

Now for an example. Use a VTVM to test the pentrode amplifier in figure 14-3—run voltage tests for possible casualties.

Notice the pin numbers at each electrode in the 6SJ7 of figure 14-3. These pin numbers tell you where to connect the meter—in the voltage test charts, each electrode is listed by its pin number.

First, measure the Eb. Connect the common lead of the VTVM to the chassis, and connect the test probe to test point 8.

If the Eb measures too HIGH, move the test prod to test point 5 and read the Rk voltage. If the Rk voltage is also too high, Rk is responsible for the high Eb reading. Probably Rk has increased in value due to aging or overheating. You've pinpointed to casualty at Rk—replace Rk.

On the other hand, if the Rk voltage measures too LOW, the tube is responsible. Probably the cathode emission has decreased due to aging. Replace the 6SJ7 tube.

There are other casualties that could be responsible for a high Eb reading. An open Rsg or a leaky Csg would DECREASE the screen grid voltage. The decreased screen grid voltage would decrease Ip, causing too high an Eb reading. A loss of resistance in RL or Rd would also cause a high Eb.

Test for a leaky Csg by measuring the screen grid voltage at test point 6—with the 6SJ7 removed. If Csg is OK, it will quickly charge, and the VTVM will read the Eb—270 volts. But if Csg is leaky, it will draw current through Rsg, and the VTVM will always read LESS than 270 volts.

Tests for an open in Rsg by measuring the screen grid voltage—with the 6SJ7 in place. If Rsg is OK, the voltage at the test point will be

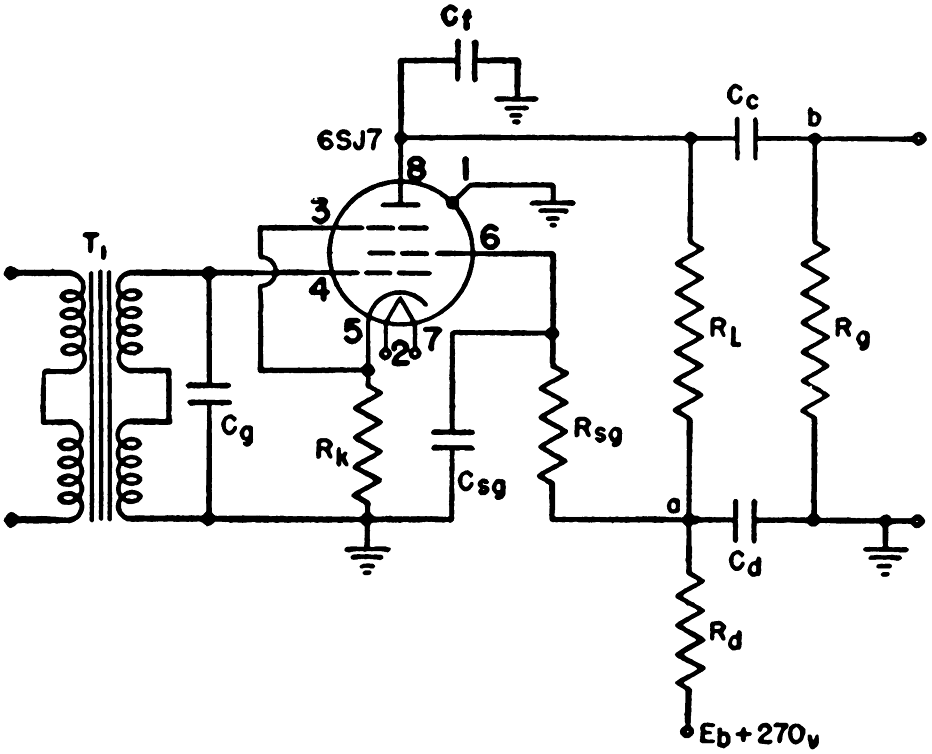

Figure 14-3.—Pinpointing by voltage tests.

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STANDARD. But if Rsg is open, the VTVM will read ZERO. If Rsg is shorted, the VTVM will read the Eb.

Now, assume that the Eb reading at test point 8 is too LOW. Again, you'd measure the Rk voltage at point 5. If the Rk VOLTAGE is too high, you'd know that TOO MUCH Ip is flowing through the d-c plate circuit.

Too much Ip could be caused by a loss of bias. Since you've already checked Rk, the loss of bias must be in the grid circuit. Measure the bias between points 4 and 5. If the grid circuit is complete, the bias between points 4 and 5 should be equal to the Rk voltage between point 5 and ground. If the grid circuit is open, the bias between points 4 and 5 reads zero. Probably the open is in the secondary of T1—replace T1.

An increase in the resistance of RL or Rd can also cause a decrease in Eb. Three types of capacitor casualties can cause a low reading at point 8. If either Cf, Cd, or Cc is leaky or shorted, Eb will DECREASE.

Here's a quick test for all three of these condenser casualties. REMOVE the 6SJ7 and test the Eb at point 8. If the Eb is LESS than 270 volts, one of the three condensers is a casualty.

To pinpoint the bad condenser, move the test prod to point a. If the VTVM reads the SAME voltage at point a and point 8, no current is flowing through RL, and Cd is leaky—replace it.

If the voltage at point a is higher than the voltage at point 8, Cd is probably good, and either Cf or Cc is the casualty.

Shift the test prod to point b. Any voltage at point b means that Cc is leaky or shorted. Replace Cc.

On the other hand, if the voltage at b is ZERO, Cf is the leaky condenser—replace it.

There's one catch to the measurements at point b—a gassy tube in the next stage would cause b to test positive. However this gassy tube would not account for point 8 being less positive. You can avoid any mistake by removing the tube in the next stage. If the voltage at point b remains the same or rises after the tube is removed, Cc is the only casualty.

There's one other reading you could get at point 8 with the tube in the socket—the full 270 volts of Eb. A voltage of 270 volts at point 8 means either an open Rk or a bad 6SJ7. An open Rk would show up as NO VOLTAGE from point 5 to point 8. If Rk tests good, replace the 6SJ7 tube.

Now think back over those voltage tests—they have pinpointed most possible casualties. Notice that the pinpointing was done without disconnecting a single part—that SAVES TIME.

Pinpointing by voltage tests saves time, but YOU have to REASON OUT the casualties—YOU have to KNOW what off-standard readings MEAN. If you're not sure about voltage testing, go back to figure 14-3 and check through this amplifier again. Follow each step in pinpointing the possible casualties.

PINPOINTING BY CONTINUITY TESTS

Continuity tests are also used in the troubleshooting procedures. Continuity tests also pinpoint a casualty at the one defective circuit or part.

The OPs and ODs give you the continuity tests arranged in charts. These charts show the test points, the standard readings, and the probable casualties for off-standard readings.

All continuity tests are based on these three basic principles:

1. All negative electrodes—cathode, control grids, and suppressor grids—should have a conductive circuit through the tube socket to Eb. Each of these circuits has a standard resistance that can be measured by an ohmmeter.

2. All positive electrodes—plates and screen grids—should have a conductive circuit through the tube socket to Eb+. Each of these circuits has a standard resistance that can be measured by an ohmmeter.

3. There should be a conductive circuit between all positive terminals. And there should be a conductive circuit between all negative terminals. Of course, this principle is true only when all tubes are excited by the same power supply.

NOTE: Unless otherwise specified, it is normal practice to short all d-c voltage sources to ground when making continuity checks. This practice will prevent accidental reading of other resistances which may be in parallel with the circuit under test.

The continuity tests are made with an ohmmeter—that is, you measure the resistance of the conductive circuits. Nearly all the continuity tests can be made at the tube socket terminals.

Here's a tip that applies to all continuity tests on resistors. Don't forget the tolerance. Don't expect the resistance reading to be any more exact than the tolerance indicates. Also, consider the accuracy of the ohmmeter—seldom better than 5 to 10 percent.

Now study an example of pinpointing by continuity tests. Look at figure 14-4. This is your

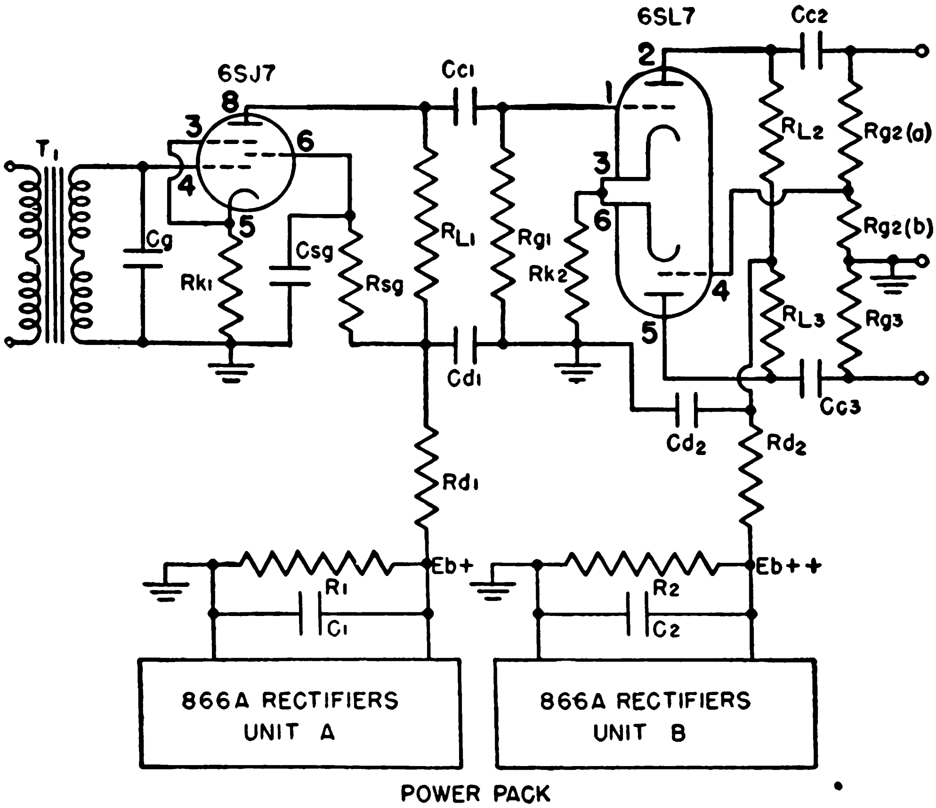


Figure 14-4.—Pinpointing by continuity tests. 55.308

example—its the first two stages of a typical motor amplifier.

Deenergizing the power pack is your first step in pinpointing by continuity tests. Jumper Eb+ and Eb++ to ground.

Next, remove all the tubes. This exposes the sockets so that all tests can be made from the top of the chassis.

Start at the input to the 6SJ7. Connect the ohmmeter across the T1 primary. You should get a fairly low reading—a few hundred ohms. A reading that's too low indicates a short, and a high reading (infinity) indicates on OPEN.

Next, connect one lead of the ohmmeter to ground, and the other to pin 4 of the tube socket. Once Cg has charged, you read the resistance of the T1 secondary. You should get a fairly low reading—again, a few hundred ohms.

A reading of infinity at pin 4 indicates an open in the T1 secondary, but too low a reading indicates a short in either Cg or in the T1 secondary. If you get a low reading at pin 4, disconnect one lead of Cg. Then test Cg and T1 separately.

Move the test prod to pin 3 and then to point 5. At each pin, you should read the resistance of Rk1. Too high a reading indicates an open Rk1.

Move the test prod to pin 8. You should read the combined resistance of RL1 and Rd1. A reading of infinity at pin 8 indicates an open in either RL1 or Rd1, and too low a reading indicates a partial short in either RL1 or Rd1.

Move the test prod to pin 6 of the 6SJ7. Notice the ohmmeter leads are across Csg in parallel with Rsg and Rd1. You should get an initial deflection of the meter as Csg charges. The final reading should be close to the combined resistance of Rsg and Rd1. If this reading is low, Csg may be shorted or leaky; or one of the resistors may be at fault.

The next step is to disconnect Csg and test pin 6 again. If the reading is correct, Csg is at fault. Replace Csg. If the reading was incorrect, check Rsg and Rd1 separately and replace the faulty component.

To test Ccl and Cdl, you must disconnect one of the leads. Connect the ohmmeter directly across either one of the condensers. They should test infinite or at least 50-60 megohms resistance.

That completes the tests for casualties in the first stage. Now run through the second stage—the 6SL7.

Move the test prod from pin 3 or pin 6 to pin 1, and finally to pin 4. Pin 3 or 6 reads the resistance of Rk2. Pin 1 reads the resistance of Rgl and pin 4 reads the resistance of Rg2(b).

Move the test prod to pin 2 and read the combined resistance of RL2 and RD2.

Move the test prod to pin 5 and read the combined resistance of RL3 and RD2.

Now test the second stage capacitors Cd2, Cc2, and Cc3 in the same manner that the capacitors in the first stage were tested.

Before you leave continuity tests, give them a review. First of all, each circuit to be tested contains either a capacitor or a resistor. The ohmmeter measures the resistance of the capacitor or a resistor and the continuity of the circuit. A high ohmmeter reading means too much resistance—an open; and a low ohmmeter reading means too little resistance—a short or a leak.

PAINT FOR FIRE CONTROL INSTRUMENTS

Practically all fire control instrument cases are cast aluminum, with a baked enamel finish applied at the factory. This finish is hard and glossy, and the cast aluminum is especially corrosion resistant. Painting a whole instrument because of a few scratches, chips, or worn spots is generally not recommended. Normally, only instruments exposed to the weather require painting. When you do paint, follow the instructions given in the Bureau of Ships Technical Manual, NavShips 250-000.

PACKING AND TRANSPORTING

When it becomes necessary to ship or transport an instrument, it must be packaged properly to prevent shock and exposure to the elements. If possible the original shipping container should be used, since it will have the proper mountings to hold the instrument rigidly in place. Upon completion of packing, stencil the containers with HANDLE WITH CARE—DELICATE INSTRUMENT.

INSTALLATION

During the installation of fire control equipment, the weapons officer or his representative will inspect or supervise the work to see that it meets the specifications of the Bureau of Naval Weapons. Since you may be one of his assistants, you must also familiarize yourself with the necessary requirements. Many headaches can be avoided if the initial installation is correct and the proper inspections are made at the time of the installation. Don't hesitate to report any discrepancies you note to the weapons officer.

WEAPON CONTROL SYSTEM TESTS

Weapon control system tests apply to all the equipment necessary to secure consistently satisfactory performance. These tests vary according to the installation, so you will have to consult the applicable ordnance publications for detailed information. In this course, we will discuss in general terms the routine tests you are required to perform or know about. These tests are:

1. transmission tests
2. computer tests
3. operational test of equipment not included above
4. dynamic tests
5. system alignment tests

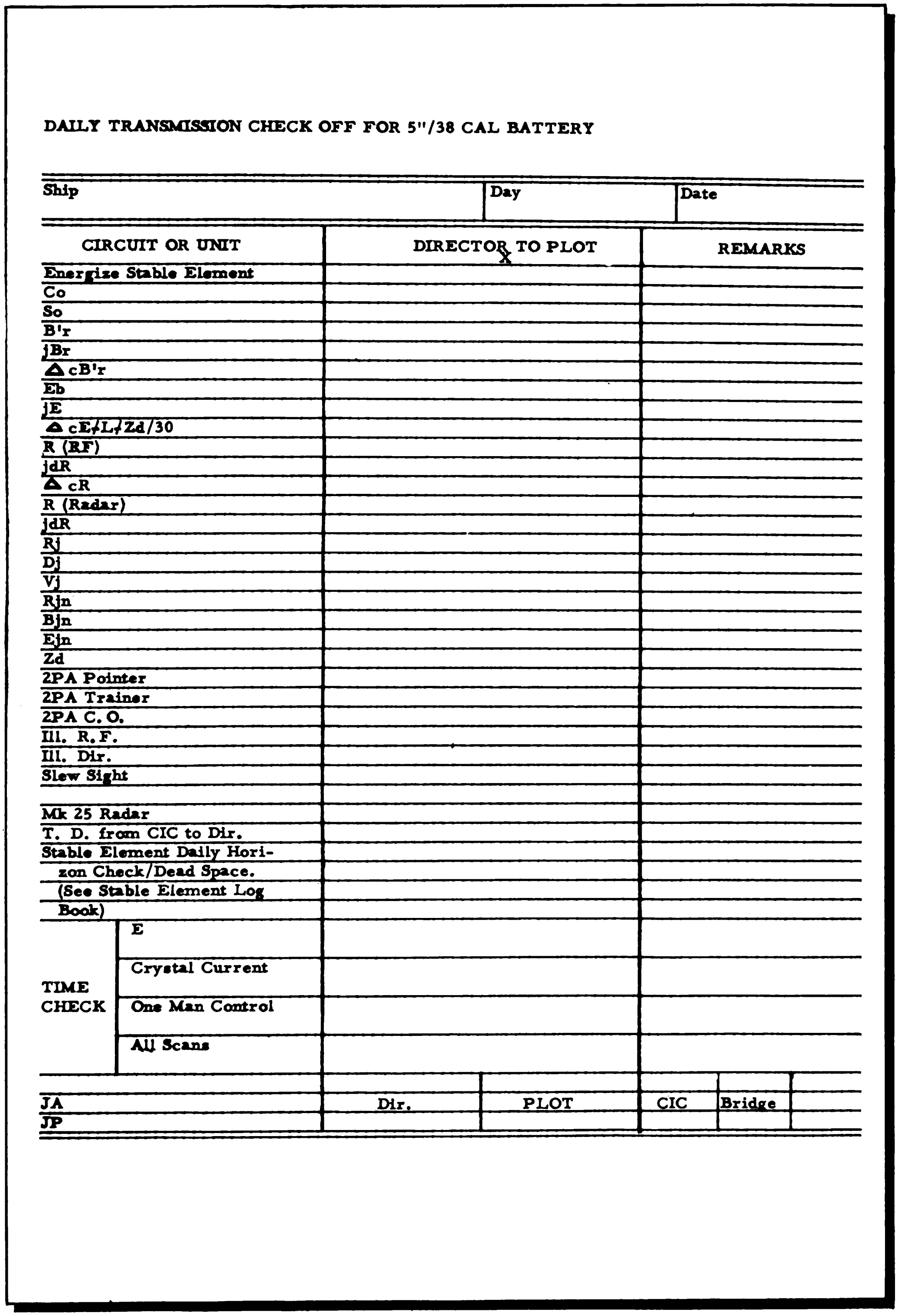
TRANSMISSION TESTS

The transmission test is held daily. It tests the accuracy of the information flow between instruments and stations, and the response of automatic control devices and power drives to changing signals. In addition, many routine daily checks are included. Figure 14-5 is a portion of a transmission checkoff sheet. From the illustration you can get a good idea of the type of items checked in this test.

Daily operation of the system in all modes of control exercises the servosystems, power drives, and computing networks. These exercises help to avoid some casualties and detect existing casualties.

COMPUTER TESTS

This section deals with the various periodically conducted tests of the computer. A fire control computer solves a particular type of problem. To test the computer's accuracy, it is given



DAILY TRANSMISSION CHECK OFF FOR 5"/38 CAL BATTERY

Ship	Day	Date

CIRCUIT OR UNIT		DIRECTOR TO PLOT	REMARKS
Energize Stable Element			
Co			
So			
B'r			
jBr			
Δ cB'r			
Eb			
jE			
Δ cE+L+Zd/30			
R (RF)			
jdR			
Δ cR			
R (Radar)			
jdR			
Rj			
Dj			
Vj			
Rjn			
Bjn			
Ejn			
Zd			
2PA Pointer			
2PA Trainer			
2PA C. O.			
Ill. R. F.			
Ill. Dir.			
Slew Sight			
Mk 25 Radar			
T. D. from CIC to Dir.			
Stable Element Daily Horizon Check/Dead Space. (See Stable Element Log Book)			
TIME CHECK	E		
	Crystal Current		
	One Man Control		
	All Scans		

JA	Dir.	PLOT	CIC	Bridge	
JP					

Figure 14-5.—Daily transmission checkoff for 5"/38 battery.

55.309

a series of problems to solve; its answers are compared with answers calculated by other means.

When you track a moving target, the inputs to the computer are continuously changing. The computer uses instantaneous values of the inputs to solve the ballistic computations and predict future target position. Therefore, the computer's solution is based on an infinite number of static (standstill) problems. When the relative motion rates are integrated with time to generate the computer changes in target position, the problem becomes dynamic. Consequently, the tests are of two types—static and dynamic.

Static Tests

Static tests check the overall operation of the computing system in a standstill condition. Static tests vary with different types of solutions of the fire control problem. In the linear rate solution, the computer solves for linear rates of relative motion and their computation is included in the test. In this type of computer, the static tests are called "A" test. In the angular rate solution, the predictions are based on measured angular rates rather than computed rates. The rate measurements are not checked by the static test, but they are used as inputs during the test.

The relative motion rates vary with changes of range, bearing, or elevation. It is necessary, therefore, to take a "snapshot" of the computing system during the operation of tracking a target. In linear rate computers, this "snapshot" condition is obtained by turning off the time motor and setting in the test values. In angular rate systems, in order to "freeze" the computing system at a certain point in the travel of a moving target, predetermined values of the angular rates are introduced.

Dynamic Tests

Static tests check all the computations except those involving generation. Generation is checked by the dynamic tests. Dynamic tests vary with the type of solution of the fire control problem. In the angular rate system, the rates are measured by a device with gyroscopic properties. A check of the measuring device would have a function somewhat similar to the dynamic tests used to check generation in a linear rate computer. The measuring device is checked by tracking a target.

In the linear rate computers, generation is checked by the "B" and "C" tests.

"B" and "C" Tests

The "B" test offers the most direct test of a generated quantity, but it cannot be used on a regenerative machine like the Rangekeeper Mk 8. It is used on nonregenerative machines such as the Computer Mk 1A. The "B" tests check the computer's generation of bearing, elevation, and range for specified time intervals with that of a mathematical solution whose answer contains the correct amounts of change in the quantities for the same conditions. During the test, fixed values are assigned to the relative motion rates. This is done by manually setting the inputs to the relative motion group. The time system of the computer is moved, either manually or by the time motor, by an amount equal to the test interval. Readings are then taken at the generation dials. The "B" tests consist of three sets of problems: one set for bearing, one set for range, and one set for elevation.

In a regenerative machine the generated changes feed back into the relative motion group, changing the values of the rates which were originally introduced. Therefore, the "B" test cannot be used on this type of machine. In its place, and for the same purpose, the "C" test is used. In the "C" test the changes to range and bearing are read.

In the "B" and "C" tests two types of errors are considered—the difference error and the rate error. The difference error is the difference between the dial reading and the calculated value.

The difference error alone does not tell you much, because it depends on how long the problem is run. The rate error tells you the amount of error per unit of time, usually a minute. The rate error is obtained by dividing the difference error by the length of time the problem has run. The sign given the rate error is determined by the amount of generation per unit of time. Too much generation is given a positive sign and too little generation is given a negative sign.

Rate Control Tests

The rate control tests check the functioning of the rate control system. The mechanisms of this system correct target angle, target speed, and rate of climb, so that the computer target motion rates agree with the actual rates of the target. In other words, this is a test of the time required for the computer to arrive at the correct relative motion rates. The time required must be small, but smoothness of tracking must be considered. The rate control system is a compromise between these two factors.

The rate control tests consist of tracking a hypothetical motionless target with the computer set for a selected sensitivity of rate error detection. The sensitivity is controlled by the time constant input to the rate control system. Initially a large error is introduced and the time motor started. The time required to reduce the error by a preselected amount of percentage is timed by a stopwatch. The stopwatch reading is a measure of the actual time constant or sensitivity of the system, and is compared with the theoretical value for the test.

OPERATIONAL TESTS

Operational tests are among the most important checks of the fire control equipment. The final test of your equipment is its operational performance. All fire control equipment should be tested periodically, as both an individual unit and a part of the system. To hold these tests correctly, the operators must be thoroughly familiar with the operating characteristics of the equipment in all types of control. Following is a list of a few items that will not necessarily be checked by the other tests, although they can and should be tested by the operators on stations.

1. The entire system tracking a target.
2. Target designation system or weapons directional equipment and all indicators.
3. Interbattery connections and flow of information.
4. Special purpose computers: starshell, shore bombardment, wind, parallax.
5. Optical equipment—rangefinder and rangefinder operators, stabilizers, lead-computing sights. The operational performance of fire control equipment is described in the OPs on the system and units.

DYNAMIC ACCURACY TESTS

The alignment and transmission test check the system at rest. But the director and guns are always in motion when following a moving target, and it is important that they be in alignment not only when stationary but when moving in response to a dynamic signal as well. Thus it becomes necessary to determine the accuracy with which a director or gun responds to a continually changing signal, such as generated bearing or gun orders. The dummy director and error recorder (fig. 14-6) were developed for this purpose; they provide a means for transmitting an automatic signal to a gun or director

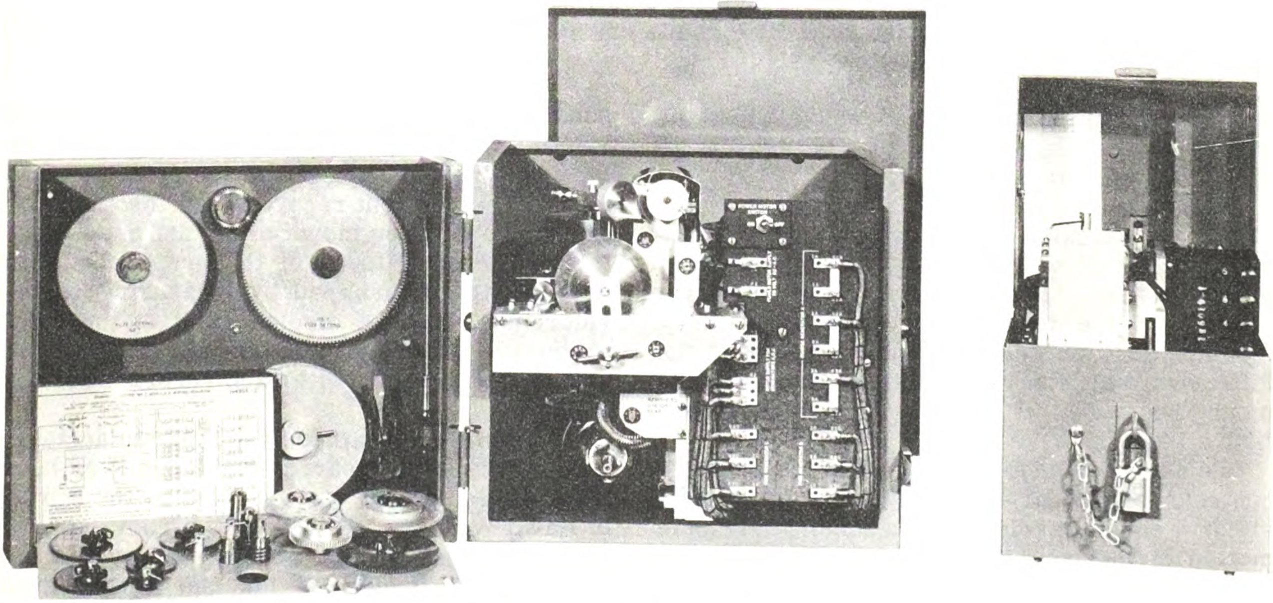


Figure 14-6.—Dummy director and error recorder.

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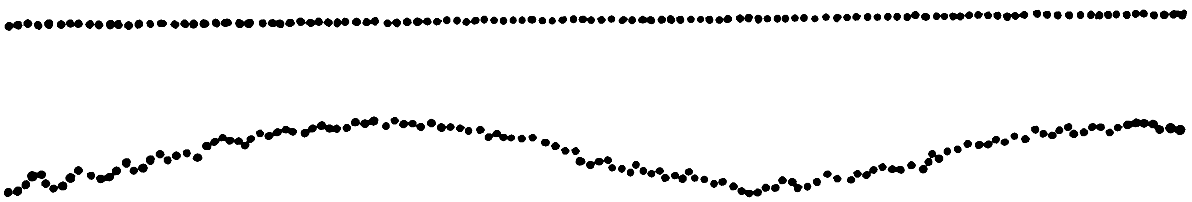
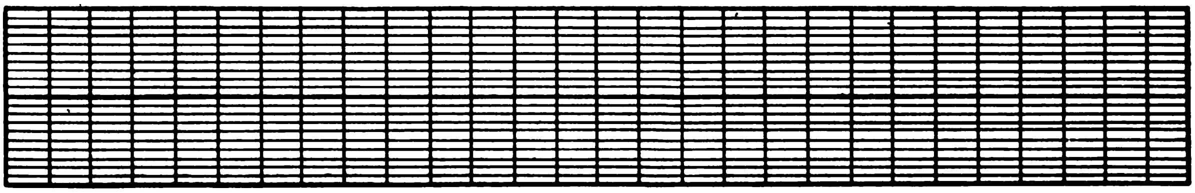


CURVE OBTAINED FOR 25-DEGREE ROLL FOR 9-SECOND PERIOD
(This curve represents an error of 9 minutes of arc)



TRANSPARENT SCALE FOR COMPARISON OF CURVE

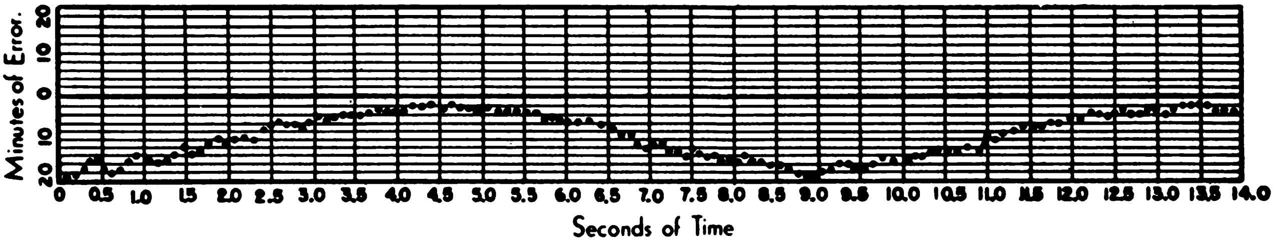


Figure 14-7.—Sample error recorder strip.

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simultaneously measuring the amount that the gun or director lags the signal. These tests are called dynamic accuracy tests.

The dummy director introduces angular motion electrically into the system under test—either constant velocity motion or simple harmonic motion. The error recorder makes a record of the test in the form of a time-displacement curve. The curve indicates the difference between the signal to the mount and mount response. A sample curve is shown in figure 14-7:

To test a director, gun, or turret in remote control, electrical signals (corresponding to either a constant velocity or a simple harmonic motion of the mount) are transmitted from the dummy director to the remote control equipment at the mount and to the error recorder. The error recorder also receives a signal corresponding to mount response from the gun or director under test. As the mount moves in response to the changing signal, the error recorder makes a permanent record of the instantaneous difference between mount order and mount position. The magnitudes of the errors in mount position are determined by measuring (from a reference line) the displacement of the curve produced by the error recorder. Transparent scales are supplied with each recorder for this purpose.

The curves obtained by a dynamic accuracy test should be compared with the curves taken when the equipment was accepted by the Bureau of Naval Weapons. If the curves from the periodic tests show rough followup action or a response lag in excess of that specified for the particular mount, the power drive should be checked for malfunctioning.

SYSTEM ALIGNMENT

Briefly, the purpose behind system alignment is to facilitate the control of an entire battery from a single controlling station. Where more than one battery and control system is installed, the batteries and control systems are inter-aligned to provide greater flexibility. Alignment is an involved procedure, and we will not go into details in this course. It will be covered in a later course of this series.

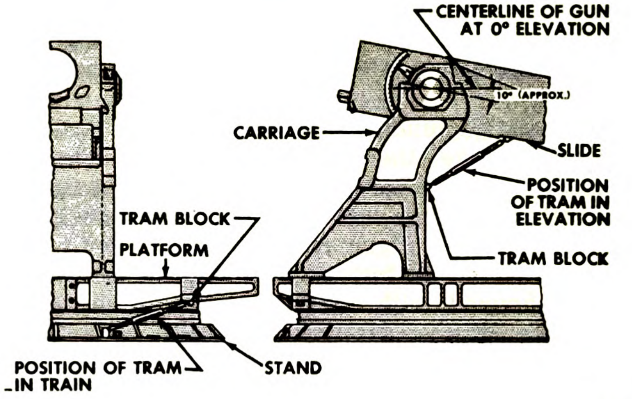
Since the alignment procedures covered here are applicable to any group of weapons and control equipment, the term "element" is used to designate a unit of an installation. The term "element" may mean a director, gun mount, launcher, or other unit of ordnance equipment.

The alignment procedures are of two kinds—internal alignment and system alignment. Internal alignment is the procedure for aligning an element within itself. This will not be covered here but can be found in the equipment's OP.

System alignment consists of aligning the elements of a group with each other. System alignment is performed in two stages. The first stage is initial alignment, which is performed by the Navy yard. The second stage is alignment afloat, which is performed by ship's force.

Initial Alignment

Initial alignment is usually performed with the ship in drydock, resting on the keel or partially waterborne. Each element is aligned in train with respect to the ship's centerline. The inclination of each element's roller path is measured and corrected to a preselected reference plane. The reference plane may be an imaginary plane or the plane of the roller path of one of the elements. The elevation of each element is aligned to its roller path, which in turn is corrected to the reference plane. Thus the elevation of each element is aligned to a common reference plane. If all the elements are aligned to the same reference, they will be aligned to each other. Bench marks and tram blocks are installed, as shown in figures 14-8 and 14-9, to provide a permanent reference for future alignment.


CENTERLINE OF GUN AT 0° ELEVATION
10° (APPROX.)
CARRIAGE
SLIDE
POSITION OF TRAM IN ELEVATION
TRAM BLOCK
PLATFORM
TRAM BLOCK
POSITION OF TRAM IN TRAIN
STAND

55.312

Figure 14-8.—Tramming the 5"/38 gun mount.

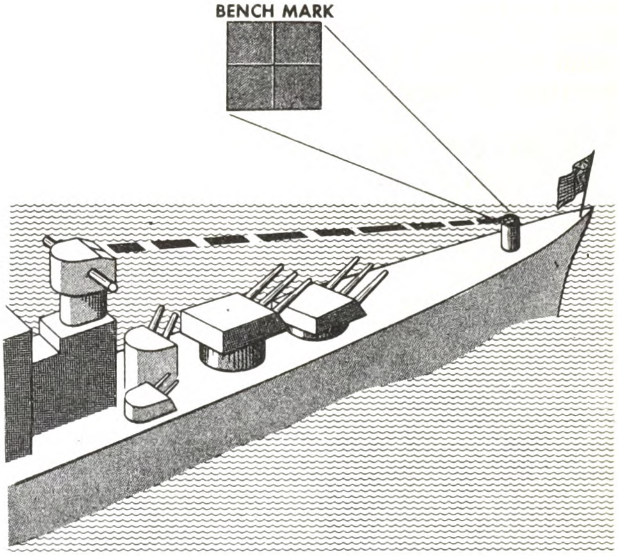


Figure 14-9.—Bench mark. 55.313

System Alignment Afloat

Alignment afloat is performed with the ship in full operating condition; it is the final alignment procedure. How well this job is done will show up during firing. Alignment afloat is necessary because the ship's hull changes shape when waterborne. These changes in hull shape can cause errors in alignment.

Before you start to align the system, a check of all the elements in the system should be made. Each element should be working properly, and its internal alignment completed. A transmission check should be made to ensure correct information flow throughout the system.

The job requires that we check train and elevation alignment between all elements, and that all roller paths are corrected to the reference plane. The information supplied by drydock alignment is bench mark and tram readings, an established reference plane, and a reference element.

Train alignment can be checked on a target at infinite range—the moon for example. The advantage of using a target at infinite range is that parallax does not enter into the alignment check.

Elevation alignment can be checked in the same manner as train. But the angle of elevation is measured with respect to the roller path; therefore the parallelism of the roller paths must first be checked. This is done at sea by a horizon check. In taking the horizon check, the idea is to sight the director and gun on the horizon at numerous bearings to see if all lines of sight (LOS) pass the horizon simultaneously. The gun's angle of elevation is changed until this occurs and the dial readings are recorded. The dial readings are compared and plotted. The results of the plot tell us two things—(1) the constant difference is an elevation error, and (2) the varying difference is the roller path error.

WEAPONS DIRECTION EQUIPMENT AND TARGET DESIGNATION SYSTEM TESTS

The names associated with the systems are descriptive of their functions. The primary function of the target designation system (TDS) is to provide designation to its associated fire control systems. The weapons direction equipment (WDE) goes beyond this and is designed to exercise command functions and control over weapon selection and the weapons themselves. In either case, both systems are the connecting link between the target detection devices, such as the search radar, and the fire control systems (FCS). Unfortunately, the installations aboard ship are so varied that a detailed description of a WDE or TDS system check is not possible here. Due to this very fact, however, a generalized discussion is in order. It will be necessary for you to associate this information with your installation. Study the flow diagrams of your system and the functional description of its units.

POWER SUPPLY CHECKS

The operation of this equipment depends on the correct power being available. Therefore, you naturally would start the system test with a check of the power supplies. There are three sources of power to be checked. The first is the line voltages of the ship's power inputs. Their presence is normally indicated by a power-available light or built-in meters. The second is the internal power supplies, which generate the voltages and potentials needed in the system's units. The third is the reference voltages, such as synchro supply. The reference voltages have a phase relationship or potential common with another system. Be careful when working around the reference voltages; frequently they bypass the unit's power switch, and voltage may be present even though the power switch is off.

The type, number, and value of the voltage inputs and internal power supplied in your system can be found in the equipment's OP. The power supply checks will be included. Before leaving this section of the system checks, test yourself to determine if you know all the voltages present and their sources.

CONSOLE DISPLAY CHECKS

The consoles display to a varying degree a graphic picture of the tactical situation about own ship. This information is displayed by the use of lamps, dials, and video indications on cathode-ray scopes (CRT). The lamps are used to indicate information that has only two states. An example of this type information is "power on" (lamp on) or "power off" (lamp off). Dials give a quantitative value to the information displayed. Examples of this type of information are range and bearing. To check this type of information you check its presence and see that it is indicating the correct value. Video indications consist of information received from the detecting devices, repeat backs from the associated FCSs, ship's course, and symbols or indications generated within the WDE or TDS systems. To check the video indications it is necessary to know the operation and function of the unit. The systems are flexible, and the number of stations supplying information will vary with different installations. For a complete test of the console display, you should check the information from all its possible sources.

OPERATIONAL TEST

The operational test is a check of the equipment's functional performance as a system. Both the TDS and WDE systems have common functions which can be listed under the follow broad headings.

1. RECEIVES information from associated equipments.

2. CONVERTS this information to the proper reference frame and coordinate system.
3. DISPLAYS the information for evaluation.
4. TRACKS the target's video indication to provide a continuous description of target's position.
5. TRANSMITS designation information to assigned associated equipments.

In some WDE systems the evaluation is done in stages at separate consoles, and automatic target tracking is employed. Also in the WDE systems, the assignment procedure involves both the FCS and weapon to be used on a selected target.

The operational test begins with a functional check of each unit in your system. Each unit has a definite job or step to perform. In most cases the function of a unit can easily be determined. The operation and function of the units are described in the applicable OP. To do its job the unit must receive from various sources the necessary data. Data flow is shown in the ship's plans and diagrams of your system. After the tests of the individual units have been completed, a system operational test is performed.

FIRE CONTROL SWITCHBOARDS

The FC switchboard is the nerve center of the ordnance equipment aboard ship. The switchboard energizes the control circuits of the FC system. A typical FC switchboard is shown in figure 14-10. The rotary switches transfer control of certain circuits from one station to

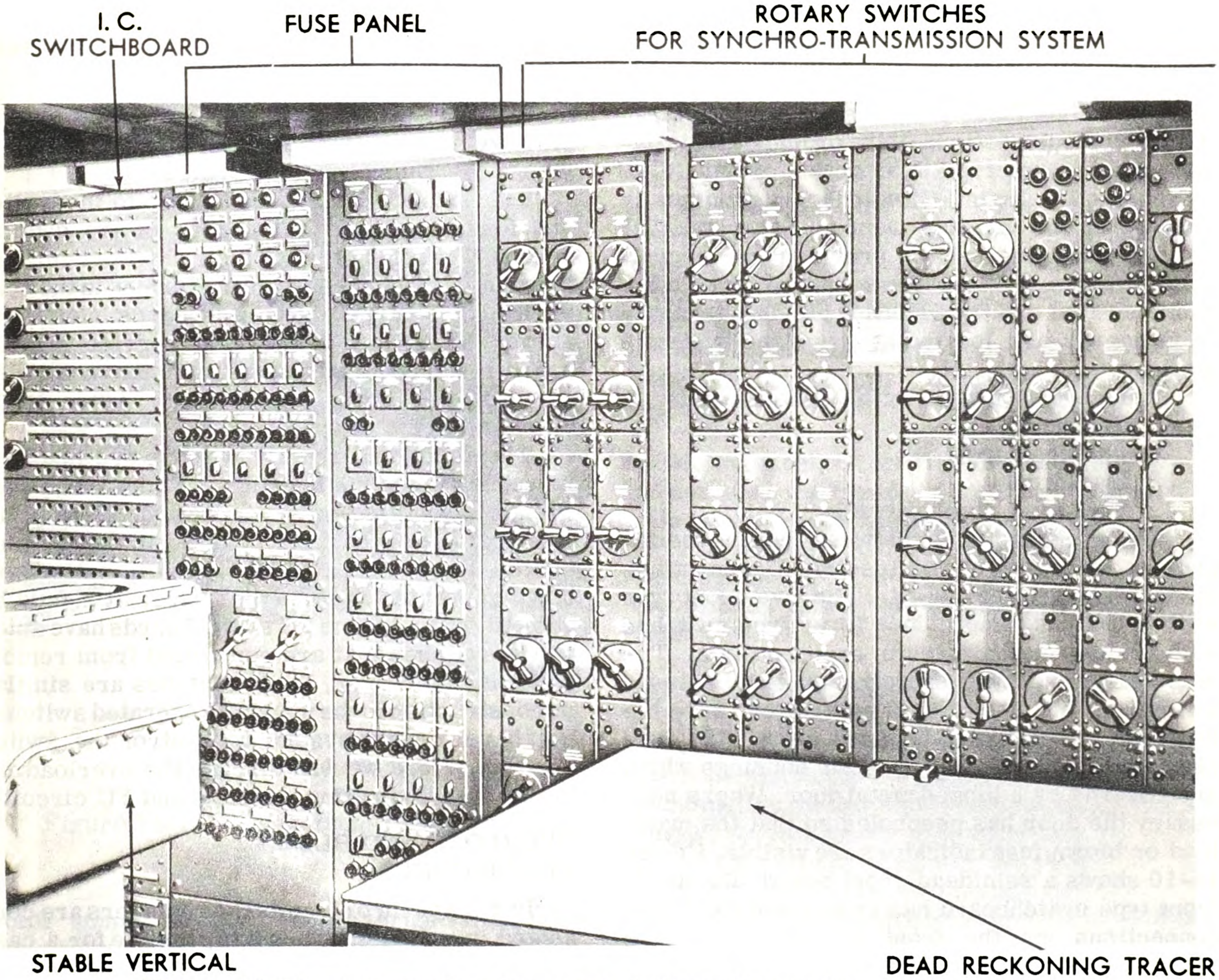


Figure 14-10.—A typical cruiser main battery fire control switchboard. 55.314

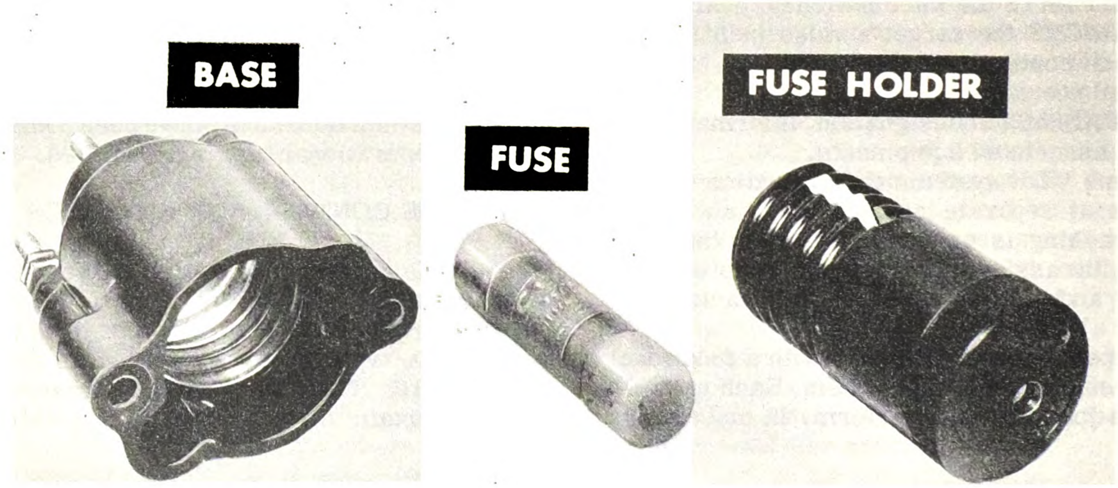


Figure 14-11.—Fuse holder assembly. 55.315

another. Thus these switches permit the isolation of various portions of the ordnance installation and are referred to as action cutout (ACO) switches. The main FC switchboard is normally located in the plotting room. Separate ACO switchboards are usually provided for specialized systems such as the sound-powered telephone system and the GFCS Mk 56. The separate ACO boards are located at one of the system's stations.

There are four types of FC switchboards:

1. live-front
2. semidead-front
3. dead-front
4. dead-front front service

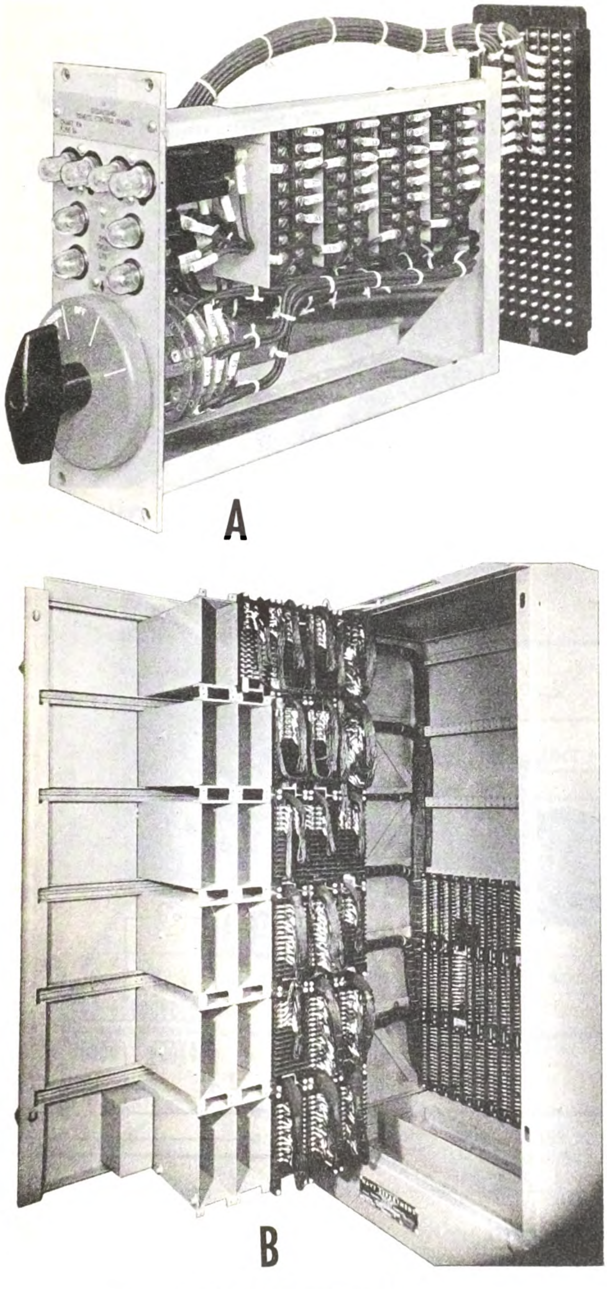
The main distinction between them is the degree of exposure of the electrical connections on the front of the board. The live-front type switchboard has knife blade lever type switches with the associated fuses in exposed clips. The semidead-front type switchboard has enclosed switches, but the fuses associated with the switches are mounted in open clips. The fuse clips are mounted in recessed housings which are covered by a hinged metal door. Where necessary the door has peepholes so that the overload or blown fuse indicators are visible. Figure 14-10 shows a semidead-front board. The dead-front type switchboard has no exposed electrical connections on the front of the board. The switches are of the enclosed type. The fuses that are accessible from the front of the board are mounted in plug type combination fuse holder and blown-fuse indicator. An example of this type of fuse holder is shown in figure 14-11.

The ship's wiring is connected to the switch and fuse terminals in the rear of the switchboard. Therefore test of a circuit to, from, and through the switchboard is performed in the rear of the three types of switchboards mentioned above. The dead-front front service switchboard is designed so that all maintenance can be accomplished from the front. Figure 14-12 shows this type of switchboard.

The individual rotary switches are installed in separate boxlike housings. This can be seen in figure 14-12 A and B. Switch types and principles of operation were covered in the training course for FT3, NavPers 10173-A, and we will not discuss the switch types here. It should be pointed out that some FC switchboards have automatic switches that are controlled from remote stations. However, these switches are similar in construction to the manually operated switches but have a servosystem to control the switch position. Here we will discuss the overload and blown fuse indicating devices and FC circuits.

OVERLOAD AND BLOWN FUSE DEVICES

In FC synchro circuits the receivers are connected in parallel. Thus it is possible for a casualty at one station to put an entire circuit out of commission. To prevent this, the receiver's



A. Action cutout unit
B. Rear view, door open

Figure 14-12.—Dead-front front-service section. 55.316

rotor supply is fused, and overload indicators are provided in the switchboard for the synchro stator circuits.

Blown Fuse Indicators

The blown fuse indicators used in FC switchboards are normally neon or incandescent lamps. The lamp is connected in parallel with the fuse. The fuse short circuits the lamp. If the fuse blows, the short circuit is opened and the potential across the lamp becomes line voltage. The lamp lights and indicates a blown fuse. The high resistance in the indicator circuit limits current flow through the circuit.

Overload Indicators

Fire control synchro circuits are precision systems in which a slight displacement between transmitter and receiver may involve a serious error. The synchro ACO switches have overload indicators connected in the synchro's stator circuit as shown in figure 14-13.

The overload transformer (fig. 14-13) consists of two primary windings, each in series with one leg of the synchro stator. The secondary winding of the transformer is connected to a neon lamp. The transformer is a current-sensitive device. When the sum of the currents in the stator circuits exceeds a certain amount the neon lamp glows. The secondary of the transformer has numerous taps to provide a wide range of voltages for a given current. The taps selected are predetermined for each circuit.

When you operate a switchboard, watch the overload indicators. Energizing a circuit by means of a transfer switch generally results in a flash of the overload lamp, which is caused by the momentary displacement between transmitter and receiver. Continual flashing or a steady glow is an indication of a casualty.

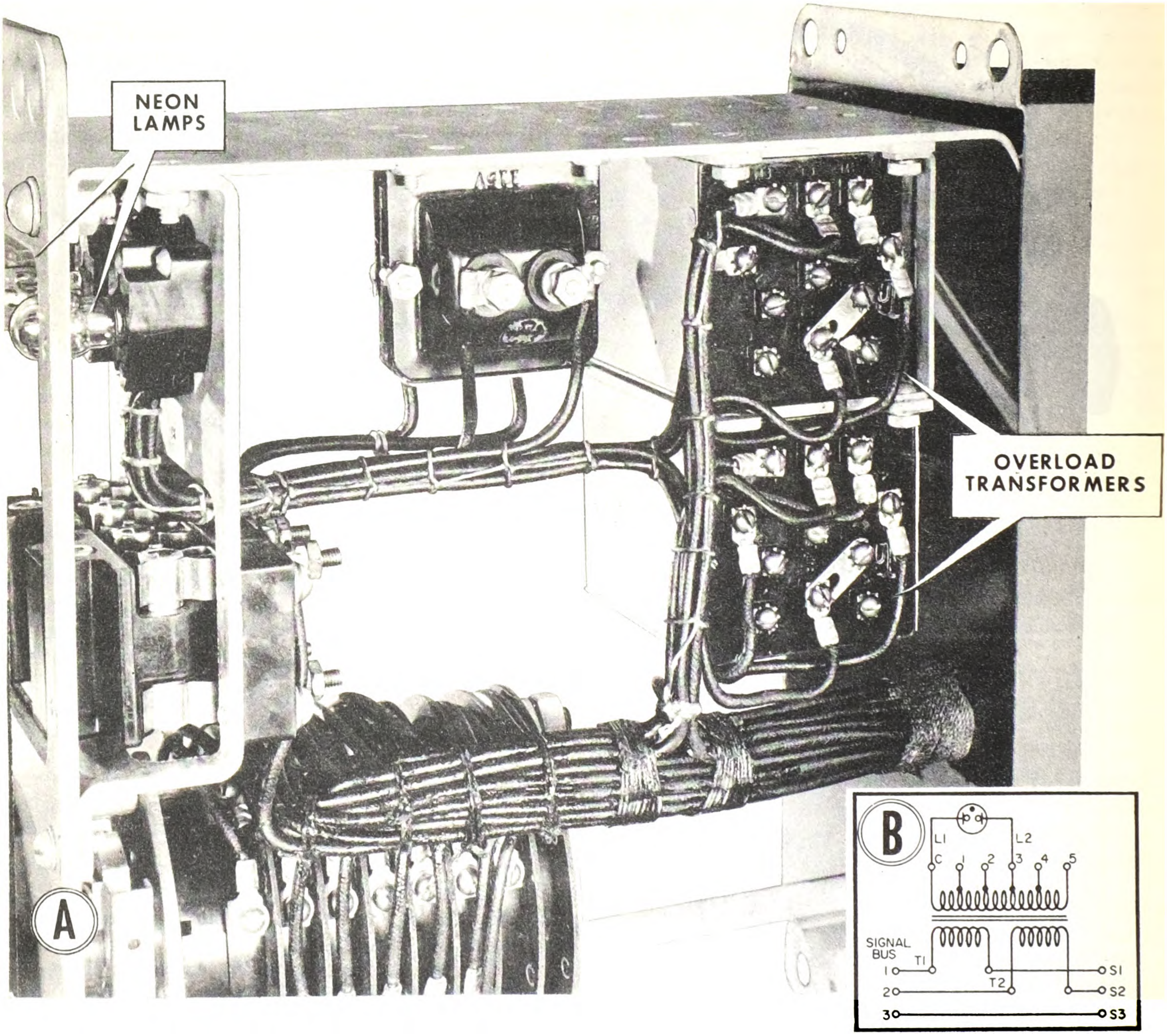
You should cut on the transmitter of a synchro system prior to its receivers. In this way, the load is placed on the transmitter at intervals.

FIRE CONTROL CIRCUITS

Fire control circuits can be identified by their designators. A designator consists of a combination of numerals and letters. For example, the designator 2GS signifies:

the numeral 2—gun train order
the letters GS—secondary battery

A list of the FC circuits and their designations and functions can be found in the Bureau of Ships Technical Manual, chapter 71.



A. External view
B. Schematic diagram

Figure 14-13.—Overload transformer.

55.317

The circuit's cables are identified in a like manner. A typical cable marking is "G-GS-21." The first G stands for the service—gunnery; the GS identifies the cable as belonging to the secondary battery; the number 21 denotes that it is the 21st cable in the GS circuits. Connection boxes are identified in the same manner as the cables.

The identification of wiring connections is a little more complicated than cable markings. A system of wire marking is used to furnish exact information. The markings are divided into three parts. The first consists of numerals which indicate the function of the wire. The second part consists of letters which indicate the circuit or system. The third part consists of numerals that indicate the station to which the wire is connected and the particular purpose of the wire in that station. The first digit in the third part indicates the station. All wires going to or within the station have the same first digit.

The majority of FC wiring furnishes power and synchro connections. Wires which furnish power use the letters in the second part of the designator to indicate the d-c polarity or assumed instantaneous a-c polarity. The return wire of a supply is distinguished by doubling the second letter (or the single letter if there is only one). In a synchro circuit the double-lettered wire is connected to R2 of the rotor. For example, 2GSS is the connection to R2 and 2GS is the connection to R1. The synchro stator connections are identified by the third part of the wire's designator. The lowest digit is connected to S1 of the synchro. If there is more than one synchro in the system, the coarse synchro has the lower three numbers.

To summarize circuit designation, we will use two wiring diagrams. Figure 14-14 shows a simplified isometric wiring diagram of the gun train order (2GS) circuit. The circuit originates in computer 1 and goes from there to the FC switchboard in cable G-GS53. The cable is type MHFA10, with 8 active leads and 2 spare leads. The active lead designators are 2GS-71, 2GSS-71, and 2GS711 to 2GS716. The circuit leaves the board in cable G-GS21. Notice that both the cable and lead designators are changed. Circuits going through a fuse, switch, or load change their designators. Any or all of the three parts of the wire marking may change. In our case the third part of the wire markings are changed; these wires are now connections to a different station in the

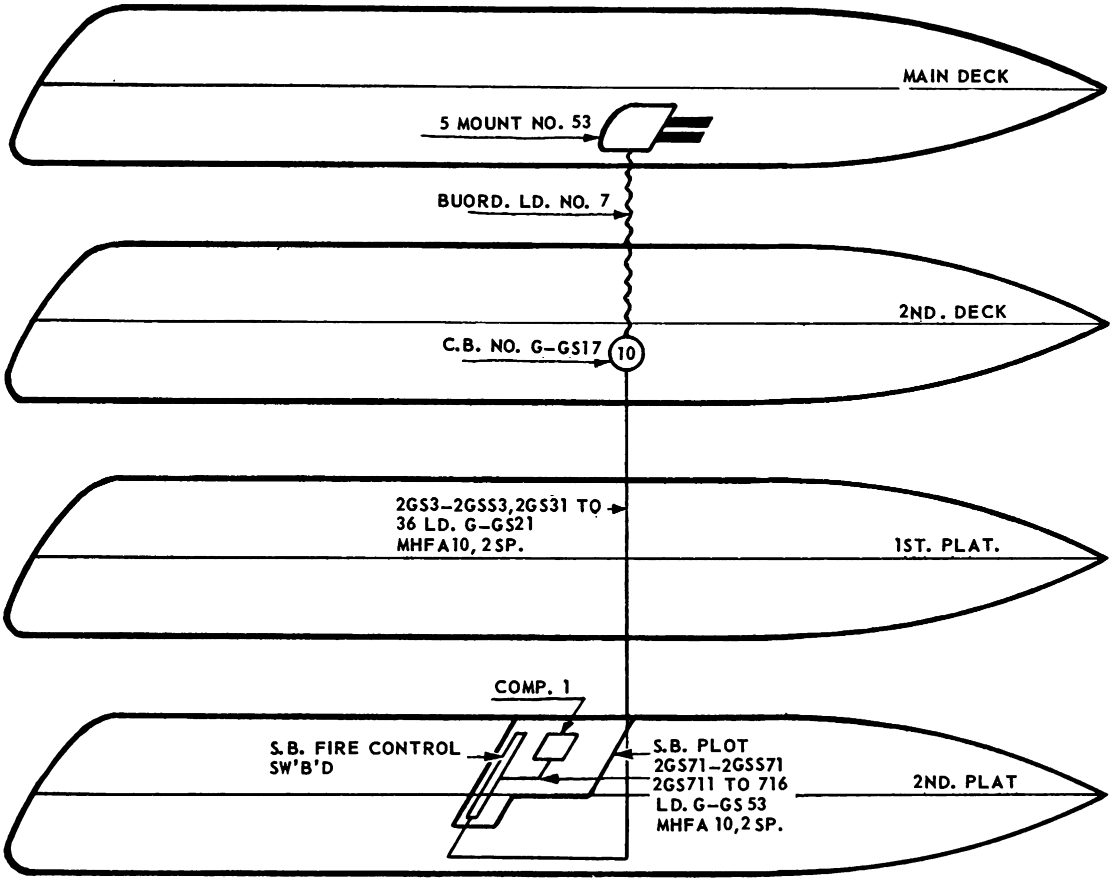


Figure 14-14.—Isometric wiring diagram.

55.318

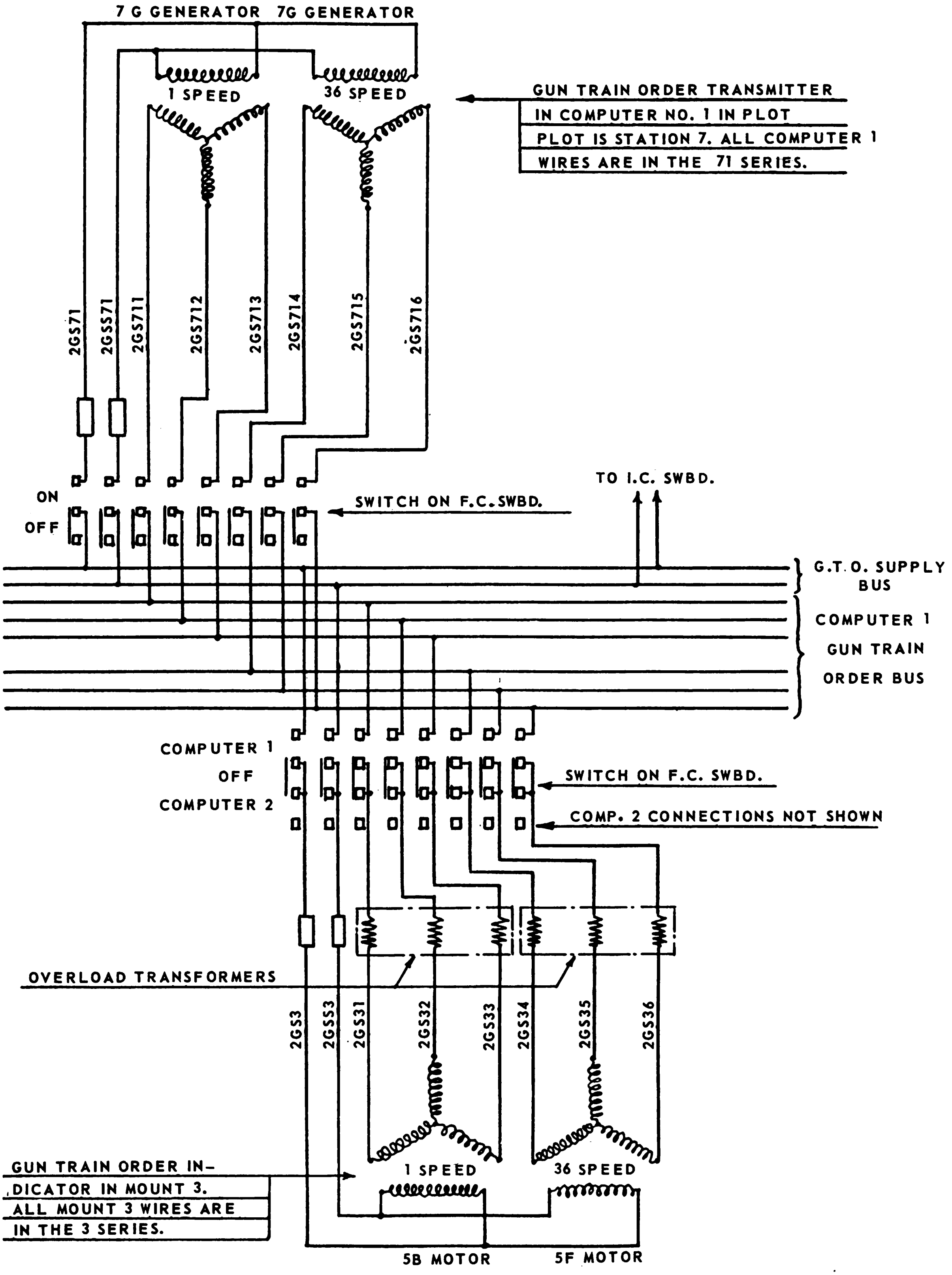
system. Cable G-GS21 carries the circuit to the 10-wire connection box, G-GS17. The circuit leaves the box in ordnance lead number 7 and goes to the 5" mount. The wavy line indicates a flexible cable.

Figure 14-15 shows a simplified elementary wiring diagram of the same circuit as the isometric diagram. Each wire is drawn and the wire marking shown. This diagram shows the circuit's functions.

Multipole Rotary Switch and Terminal Board

Multipole rotary switches and terminal blocks for FC switchboards are provided with standard wire markings for identification. For multipole rotary switches associated with terminal boards the markings, A, B, C, and so forth, are engraved on each barrier of the switch.

Terminal board markings comprise the wire designation, switch terminal designation, switch barrier marking, and the section in which the terminal is located. A typical terminal board marking is B-3-2GS71. The combination, B3, is the corresponding switch terminal designation. The letter, B, is the switch barrier marking; the numeral, 3, is the number of the switch section in which the terminal is located (the sections are numbered consecutively from the handle end of the switch); and the combination, 2GS71, is the ship's wire designation.



GUN TRAIN ORDER TRANSMITTER IN COMPUTER NO. 1 IN PLOT PLOT IS STATION 7. ALL COMPUTER 1 WIRES ARE IN THE 71 SERIES.

GUN TRAIN ORDER INDICATOR IN MOUNT 3. ALL MOUNT 3 WIRES ARE IN THE 3 SERIES.

Figure 14-15.—Elementary wiring diagram.

APPENDIX I

TRAINING FILM LIST

Training films that are directly related to the information presented in this training course are listed below. Under each chapter number and title, the training films are identified by Navy number and title and are briefly described. Those chapters for which there are no applicable training films available will not be listed. Other training films that may be of interest are listed in the United States Navy Film Catalog, NavPers 10000-A and Supplement No. 2.

Chapter 2

SERVOMECHANISM DEVICES (PART I)

MA-8581A Servo Systems and Data Transmission—Part 1—Fundamentals of Servo. (17 min.—B&W—Sound—Unclassified—1956.) US Army TF11-2235. Defines the fundamental concepts of Servo Systems, and explains the functioning of the principal Servo components. The components discussed include the Input, the Sensing Device, the Controller, the Output—Torque and Feedback.

MA-8581B Servo Systems and Data Transmission—Part 1—Principles of Positioning Servos. (33 min.—B&W—Sound—Unclassified—1956.) US Army TF11-2236. Considers positioning functions of Servo, illustrating the Servo mechanisms as integrated, operational systems.

Chapter 3

SERVOMECHANISM DEVICES PART II

MA-8581A Servo Systems and Data Transmission—Part 1—Fundamentals of Servo. (17 min.—B&W—Sound—Unclassified—1956.) US Army TF11-2235. Defines the fundamental concepts of Servo Systems, and explains the functioning of the principal Servo components. The components discussed include the Input, the Sensing Device, the Controller, the Output—Torque and Feedback.

MA-8581B Servo Systems and Data Transmission—Part 2—Basic Principles of Positioning Servos. (33 min.—B&W—Sound—Unclassified—1956.) US Army TF11-2236. Considers positioning functions of Servo, illustrating the Servo mechanisms as integrated operational systems.

Chapter 5

FIRE CONTROL RADAR

SN-1075	The Pulsing Transmitter—Radar No. 5. (40 frames—B&W—Silent—Unclassified—1942.) Explains why a special type transmitter must be used for radar; lists many advantages that ultra-short waves have over the longer waves used for regular broadcasting; outlines working principles of the transmitter.
SN-1079	The Indicator—Radar No. 9. (48 frames—B&W—Silent—Unclassified—1942.) Explains what happens when transmitter pulses; what electrical timing circuits do; how time trace is formed on the screen; and how speed of the spot of light is controlled by range setting.
MN-5050A	Radar—Accuracy and Resolution—Range. (10 min.—B&W—Sound—Unclassified—1946.) How to obtain accurate ranges from various types of radar, especially when targets are merged or nearly so. Technique of calibration, expanded scope, and reduced gain is explained. Explains range resolution.
MN-5050B	Radar—Accuracy and Resolution—Bearing. (16 min.—B&W—Sound—Unclassified—1946.) How to get accurate bearings with various types of gear. Describes and explains lobe, effective beam width, excitation level, maximum and minimum methods of attaining bearing, and use of gain in improving accuracy.

Chapter 7

TARGET POSITION AND RELATIVE MOTION

SN-3193A	Elements of a Surface Fire Control System—Part 1. (15 min.—64 frames—B&W—Sound—Unclassified—1944.) Explains why a gun cannot be pointed directly at a target in order to score a hit; defines sight angle, sight deflection, gun train, and elevation orders. Shows what three types of quantities must go into making up of gun train and elevation orders, and explains how the first of these, present position of the target, is measured.
SN-3193B	Elements of a Surface Fire Control System—Part 2. (25 min.—104 frames—B&W—Sound—Unclassified—1944.) Continues explanation started in the preceding film, showing how ballistic quantities are computed, how corrections for trunnion tilt are made, and how all these are combined to produce gun train and elevation orders.

Chapter 8

SOLVING FOR WIND

SN-3193A	Elements of a Surface Fire Control System—Part 1. (15 min.—64 frames—B&W—Sound—Unclassified—1944.)

Explains why a gun cannot be pointed directly at a target in order to score a hit; defines sight angle, sight deflection, gun train, and elevation orders. Shows what three types of quantities must go into making up of gun-train and elevation orders, and explains how the first of these, present position of the target is measured.

SN-3193B Elements of a Surface Fire Control System—Part 2. (25 min.—104 frames—B&W—Sound—Unclassified—1944.) Continues explanation started in the preceding film, showing how ballistic quantities are computed, how corrections for trunnion-tilt are made, and how all these are combined to produce gun-train and elevation orders.

Chapter 9

DECK AND TRUNNION TILT

SN-1801A The Stable Element, Mark 6—The Purpose of Stable Element. (11 min.—64 frames—B&W—Sound—Unclassified—1943.) Explains how level and crosslevel are transmitted, and how the optics respond. Discusses train and elevation.

SN-3193A Elements of a Surface Fire Control System—Part 1. (15 min.—64 frames—B&W—Sound—Unclassified—1944.) Explains why a gun cannot be pointed directly at a target in order to score a hit; defines sight-angle, sight-deflection, gun-train elevation orders. Shows what three types of quantities must go into making up of gun-train and elevation orders, and explains how the first of these, present position of the target, is measured.

SN-3193B Elements of a Surface Fire Control System—Part 2. (25 min.—104 frames—B&W—Sound—Unclassified—1944.) Continues explanation started in the preceding film, showing how ballistic quantities are computed, how corrections for trunnion-tilt are made, and how all these are combined to produce gun-train and elevation orders.

Chapter 10

GENERATED RATES

MN-7317A The Computer Mark 1A—The Mark 37 System and Tracking the Target. (22 min.—B&W—Sound—Unclassified—1952.) This film gives an outline of the complete system: the relationship of computer, director, guns and auxiliary equipment, gyro compass and pitometer log, the duties of control officer, trainer, pointer, and range operator; definitions of line of sight, line of fire, director elevation, and director train; the necessity for gun lead angles; the definitions of and dials for ship's course, ship's speed, relative target bearings, observed range, target angle, rate of climb and horizontal target speed; solution indicators; trainer, pointer, and range operator signals; relative motion rates; generated rates of target motion; rate control.

MN-7317B The Computer Mark 1A—Establishing the Line of Fire. (7 min.—B&W—Sound—Unclassified—1952.) This film shows the necessity for predicting future target position; the definitions of and counters for sight deflection, sight angle and fuze time; setting in wind corrections for wind speed and wind direction; the definitions of initial velocity and dead time; setting in ballistic corrections for initial velocity and dead time; modification of values of director train and director elevation by lead angles to produce gun orders.

MN-7317C The Computer Mark 1A—A Sample Problem. (7 min.—B&W—Sound—Unclassified—1952.) This film shows a sample fire control problem; how action above deck can be visualized at the computer; picking up target; beginning of tracking; rate controlling; technique of use and interpretation of trainer, pointer and range finder operator signals; changes in range, elevation, and bearing as problem progresses; reaching the solution; values of horizontal target speed, rate of climb and target angle at moment of solution.

MN-7317D The Computer Mark 1A—Stabilization. (12 min.—B&W—Sound—Unclassified—1952.) Movement of director and guns caused by roll and pitch; necessity for holding line of sight and line of fire independent of roll and pitch; definition of stabilization; definition of level and cross level; function of stable element; stabilization of director sights in elevation and bearing; stabilizing the line of sight; stabilization of director elevation and observed bearing for use by the computer; definition of deck-tilt correction; stabilization of line of fire production of gun orders.

SN-3193A Elements of a Surface Fire Control System—Part 1. (15 min.—64 frames—B&W—Sound—Unclassified—1944.) Explains why a gun cannot be pointed directly at a target in order to score a hit; defines sight angle, sight deflection, gun train, and elevation orders. Shows what three types of quantities must go into making up of gun train and elevation orders, and explains how the first of these, present position of the target, is measured.

SN-3193B Elements of a Surface Fire Control System—Part 2. (25 min.—104 frames—B&W—Sound—Unclassified—1944.) Continues explanation started in the preceding film, showing how ballistic quantities are computed, how corrections for trunnion tilt are made, and how all these are combined to produce gun train and elevation orders.

Chapter 11

GUN ORDERS

SN-3193A	Elements of a Surface Fire Control System—Part 1. (15 min.—64 frames—B&W—Sound—Unclassified—1944.) Explains why a gun cannot be pointed directly at a target in order to score a hit; defines sight angle, sight deflection, gun train, and elevation orders. Shows what three types of quantities must go into making up of gun train and elevation orders, and explains how the first of these, present position of the target, is measured.
SN-3193B	Elements of a Surface Fire Control System—Part 2. (25 min.—104 frames—B&W—Sound—Unclassified—1944.) Continues explanation started in the preceding film, showing how ballistic quantities are computed, how corrections for trunnion tilt are made, and how all these are combined to produce gun train and elevation orders.
SN-3193D	Elements of an Antiaircraft Fire Control System—Part 2. (17 min.—48 frames—B&W—Sound—Unclassified—1944.) Shows basic theory upon which the prediction section of the control system functions, considering such items of input or output as: advance range, predicted target elevation, linear deflection, sight deflection, initial velocity (I.V.) loss, super-elevation, sight angle, trunnion tilt corrections, gun elevation order, gun train order, and fuze time.
MN-7317B	The Computer Mark 1A—Establishing the Line of Fire. (7 min.—B&W—Sound—Unclassified—1952.) This film shows the necessity for predicting future target position; the definitions of and counters for sight deflection, sight angle and fuze time; setting in wind corrections for wind speed and wind direction; the definitions of initial velocity and dead time; setting in ballistic corrections for initial velocity and dead time; modification of values of director train and director elevation by lead angles to produce gun orders.
MN-7317D	The Computer Mark 1A—Stabilization. (12 min.—B&W—Sound—Unclassified—1952.) Movement of director and gun caused by roll and pitch; necessity for holding line of sight and line of fire independent of roll and pitch; definition of stabilization; definition of level and crosslevel function of stable element; stabilization of director sights in elevation and bearing; stabilizing the line of sight; stabilization of director elevation and observed bearing for use by the computer; definition of deck tilt correction; stabilization of line of fire production of gun orders.

Chapter 12

SUBMARINE FIRE CONTROL

MN-2850	Gyroscopic Creep and Precession in Torpedoes. (15 min.—B&W—Sound—Unclassified—1943.) Demonstrates rigidity

in space by use of a model gyro, creep, deflection, due to creep in North and South latitudes and on the equator, and balance-nut positions. Explains corrective precession, effect of earth's rotation fired torpedoes, and proper setting of the balance nut in various firing latitudes.

MN-6743 Introduction to Torpedoes. (14 min.—B&W—Sound—Unclassified—1950.) Introductory in nature and briefly reviews the following: tactical situation for which torpedo was designed; carriers of torpedoes and firing procedures of each; TBF airplane, destroyers, PT boat, submarine. Major components of torpedo are shown in sectional views: warhead; power plant; control mechanism. Three types of torpedoes shown: steam, electric, chemical. Exploder mechanism, location and operation; the effect of latitude on the aim of the torpedo is also shown.

Chapter 13

RANGEFINDERS

MN-2449A Optical Craftsmanship—Introduction to Optics. (17 min.—B&W—Sound—Unclassified—1945.) Uses animation and practical examples to illustrate principles of light waves and rays, how light is reflected and refracted, and image formation in relation to concave and convex lenses. Studies these principles as applied to optical instruments.

Chapter 14

GENERAL MAINTENANCE

MN-6942 Lubrication of Electronic Equipment. (8 min.—B&W—Sound—Unclassified—1953.) The purpose of this film is to instill among key personnel an appreciation for the necessity and importance of routine and methodical lubrication according to tried and recommended procedures.

SN-1808H Battery Alignment—Alignment of the Installation Afloat—Train—Part 1. (20 min.—80 frames—B&W—Sound—Unclassified—1944.) Explains parallax, both director and gun, and shows that in case of directors, maximum parallax exists for targets dead-ahead or dead-astern. Explains use of a reference point or of making one director the reference. Gun parallax exists between directors and gun, and the gun can set in correction in its own mechanism. Shows how to check direction of parallax and amount of parallax (unit parallax based on a 100-yard line from the reference point).

SN-1808I Battery Alignment—Alignment of the Installation Afloat—Train—Part 2. (17 min.—64 frames—B&W—Sound—Unclassified—1944.) Describes the following operations: checking the director on bench-mark evaluation; in train with and without the parallax mechanism; aligning the guns with the director; preliminary train test; complete train test; train check with the sights set.

SN-1808J Battery Alignment—Alignment of the Installation Afloat—Elevation. (14 min.—74 frames—B&W—Sound—Unclassified—1944.) Explains purposes and procedures of resetting roller path tilt correctors when a ship is afloat. Demonstrates simple elevation check, and checking the gun response in automatic.

APPENDIX II

QUALIFICATIONS FOR ADVANCEMENT IN RATING

FIRE CONTROL TECHNICIAN (FT)

Quals Current Through Change 19

GENERAL RATING (applicable to CPO only)

SCOPE

Fire Control Technicians: Maintain and repair weapon control systems (excluding surface ship underwater weapon control systems and launchers); make detailed mechanical, electrical, and electronic casualty analyses; operate, test, lubricate, inspect, clean, adjust, aline, and calibrate weapon control system components.

SERVICE RATINGS (applicable to PO3, PO2, and PO1)

SCOPES

Fire Control Technician G (Gun Fire Control) . . . . Maintains and repairs gun fire control systems and associated weapon control systems (including target designation systems) and FTG's designated SS, maintain and repair submarine weapon control systems.	FTG
Fire Control Technician M (Missile Fire Control). . . . . Maintains and repairs missile fire control systems and associated weapon control systems (including weapons direction systems).	FTM

Qualifications for Advancement	Required for Advancement to		
	FTG	FTM	FT
A. SAFETY PRECAUTIONS			
1.00 Practical Factors			
.01 Demonstrate under simulated conditions:			
a. Rescue of a person in contact with an energized (low voltage, high voltage) circuit where switches are accessible and inaccessible. . . .	3	3	-
b. Resuscitation of a person unconscious from electrical shock and treatment of electrical and acid burns	3	3	-

	Qualifications for Advancement	Required for Advancement to		
		FTG	FTM	FT
A.	SAFETY PRECAUTIONS—Continued.			
1.00	Practical Factors—Continued.			
.02	Demonstrate while servicing equipment:			
	a. Safety precautions such as tagging switches, removing fuses, grounding test equipment, using shorting bars, rubber mats, and rubber gloves	3	3	-
	b. Precautions while taking voltage measurements	3	3	-
2.00	Knowledge Factors			
.01	Effects of electrical shock on the human body and first aid associated with resuscitation such as moving victim and administering stimulants	3	3	-
.02	Regulations regarding the following: working on energized equipment, working alone, working aloft, interlocks, and intentionally taking an electrical shock	3	3	-
.03	General safety and servicing precautions as prescribed by OPNAV 34P1 and specific precautions applicable to the equipment to which assigned	3	3	-
B.	ELECTRICITY AND ELECTRONICS			
1.00	Practical Factors			
.01	Calculate current, voltage, resistance, capacitive and inductive reactance in series, parallel and series-parallel a.c. and d.c. circuits containing not more than five compounds	3	3	-
.39	Operate the following test equipment:			
	a. Multimeter (electronic and nonelectronic)	3	3	-
	b. Oscilloscope	3	3	-
	c. Tube, transistor, and crystal testers	3	3	-
	d. Megohmmeter (megger)	3	3	-
	e. Signal generator (audio and RF)	2	2	-
	f. Low frequency function generator	-	1	-
	g. Synchroscope	1	1	-
	h. Multi-channel pen-type electrical recorder	1	1	-
	i. Spectrum analyzer	1	1	-
	j. Range calibrator	-	-	C
2.00	Knowledge Factors			
.01	Military standards used in coding resistors, capacitors, transistors, crystal diodes, and other electrical and electronic circuit components	3	3	-

	Qualifications for Advancement	Required for Advancement to		
		FTG	FTM	FT
B.	ELECTRICITY AND ELECTRONICS—Continued.			
2.00	Knowledge Factors—Continued.			
.02	Basic electrical laws pertaining to voltage and current	3	3	-
.03	Operating principles and characteristics of vacuum tubes, semi-conductors, and gas tubes	3	3	-
.39	Basic principles of:			
	a. Alternating current (a.c.) motors and generators	3	3	-
	b. Synchros and resolvers	3	3	-
	c. Power supplies, filters, and power supply regulation using voltage regulator (VR) tubes	2	2	-
	d. Radio frequency (RF), audio and poweramplifier (including push-pull circuits)	2	2	-
	e. Detecting, mixing, frequency conversion and coupling circuits as associated with a fundamental receiver	2	2	-
	f. Synchro and servo loops	2	2	-
.40	Operating principles of magnetic amplifiers (half-wave and full-wave)	2	2	-
C.	OPERATIONS			
1.00	Practical Factors			
.01	Read dials and set operating controls to predetermined values on weapon control equipment	3	3	-
.02	Perform operator's adjustments and static, transmission, computing and rate tests to weapon control equipment assigned	3	3	-
.80	Compute ballistics corrections and arbitrary corrections to hit (ACTH) using standard forms and worksheets	-	-	C
.81	Demonstrate operating procedures and techniques on weapon control equipment as required to train battle station and watchstanding operators	-	-	C
.82	Act as Battery Control Officer	-	-	C
2.00	Knowledge Factors			
.01	Identify standard electrical, electronic, and mechanical symbols used in weapon control equipment diagrams	3	3	-

Qualifications for Advancement		Required for Advancement to		
		FTG	FTM	FT
C.	OPERATIONS—Continued.			
2.00	Knowledge Factors—Continued.			
.02	Elements of air and surface weapon control problems, including missile control problem	3	3	-
.40	Recognize and interpret quantities and symbols used in missile weapon control systems	-	2	-
.41	Recognize and interpret quantities and symbols used in gun and submarine weapon control systems	2	-	-
.42	Purpose and operating principles of basic computing mechanisms	2	2	-
.43	Elements of submarine underwater weapon control problems	2	2	-
.60	Types and operating principles of director and antenna power drives	1	1	-
.61	Adjustments of basic computing mechanisms	1	1	-
.62	Relationship of electrical and mechanical inputs and outputs of a radar, rangefinder, director, computer, stable element, and gun mount of a dual purpose battery	1	-	-
.63	Relationship of electrical and mechanical inputs and outputs of a launcher and missile weapon control system	-	1	-
.80	Variables and constants of initial ballistics	-	-	C
.81	Variables and constants of submarine underwater ballistics	-	-	C
.82	Data flow in a weapon control system	-	-	C
D.	TECHNICAL MAINTENANCE			
1.00	Practical Factors			
.01	Lubricate weapon control equipment in accordance with lubrication instructions	3	3	-
.02	Make tests of weapon control equipment for continuity, grounds, and shorts	3	3	-
.03	Inspect motors and generators, clean commutator and slip ring assemblies, and replace brushes	3	3	-
.40	Trace circuits through weapon control switchboards and make repairs as necessary	2	2	-
.60	Inspect and clean slip ring assemblies such as director, antenna, and stable element	1	1	-
.61	Test, adjust, and replace mechanical weapon control mechanisms	1	1	-
.62	Lubricate and perform shipboard adjustments to gyroscopes used in weapon control equipment	1	1	-
.63	Conduct all tests, including dynamic dummy director and error recorder tests, on a weapon control system, and effect repairs	1	1	-

Qualifications for Advancement		Required for Advancement to		
		FTG	FTM	FT
D.	TECHNICAL MAINTENANCE—Continued.			
1.00	Practical Factors—Continued.			
.80	Conduct battery alinement; compute and apply corrections	-	-	C
.81	Analyze transmission, alinement, computer, and rate tests to determine need for adjustment, repair, or replacement of parts	-	-	C
.82	Conduct submarine weapon control system alinement and compute and apply corrections	-	-	C
2.00	Knowledge Factors			
.01	Methods of testing resistors, capacitors, potentiometers, transformers, electron tubes, and semiconductors	3	3	-
.02	Performance, Operational, and Maintenance Standards for Electronic Equipment (POMSEE) and Satterwhite systems of preventive maintenance	3	3	-
.40	Application of resistors, potentiometers, coils, transformers, capacitors, electron tubes, and transistors in electronic stages of weapon control equipment	2	2	-
.60	Operating principles of antennas and waveguides pertinent to weapon control equipment	1	1	-
E.	FIRE CONTROL RADAR			
1.00	Practical Factors			
.01	Make operator's adjustments and checks to fire control radars	3	3	-
.40	Aline fire control radar antennas	2	2	-
.41	Perform tests and adjustments necessary for proper operation of a fire control radar	2	2	-
.80	Perform tests and checks necessary for missile/radar correlation	-	-	C
2.00	Knowledge Factors			
.01	Operating principles and characteristics of fire control radar	3	3	-
.39	Purpose of the following radar checks:			
	a. Receiver sensitivity	3	3	-
	b. Standing wave ratio	2	2	-
	c. Transmitted power	2	2	-
	d. Beacon frequency	2	2	-
	e. Spectrum analysis	1	1	-

Qualifications for Advancement		Required for Advancement to		
		FTG	FTM	FT
E.	FIRE CONTROL RADAR—Continued.			
2.00	Knowledge Factors—Continued.			
.40	Basic operating principles of the following special circuits: limiting, differentiating, clamping, cathode follower, blocking oscillator, multivibrator, coincidence amplifier, sawtooth generator, phase shifter, converter, klystron, magnetron, discriminator, and duplexer.	2	2	-
F.	COMPUTERS AND SERVO LOOPS			
1.00	Practical Factors			
.01	Demonstrate all modes of operation of the computer to which assigned	3	3	-
.40	Perform tests necessary for operation of servo and analog computing circuits	2	2	-
.41	Test and zero synchros and resolvers.	2	2	-
.60	Prepare a weapon control system for alinement by alining synchros and other data transmission and indicating/recording devices	1	1	-
.61	Trace circuits and analyze failures of servo and analog computing circuits, making replacements, adjustments, and repairs	1	1	-
2.00	Knowledge Factors			
.01	Methods of setting synchros and resolvers to electrical zero	3	3	-
.60	Operating principles of analog computers	1	1	-
G.	WEAPONS DIRECTION AND TARGET DESIGNATION SYSTEMS			
1.00	Practical Factors			
.01	Operate weapons direction or target designation systems.	3	3	-
.40	Perform operator's tests and adjust target designation or weapons direction systems	2	2	-
.60	Perform all tests, analyze failures, and effect repairs to target designation or weapons direction systems.	1	1	-
.80	Train battle station and watch standing operators on weapons direction or target designation system of own ship.	-	-	C
2.00	Knowledge Factors			
.60	Weapons direction or target designation system data flow	1	1	-

Qualifications for Advancement		Required for Advancement to		
		FTG	FTM	FT
H.	GYROS, STABLE ELEMENTS, RANGEFINDERS, AND DIRECTORS			
1.00	Practical Factors			
.01	Conduct shipboard tests of lead computing sights	3	-	-
.40	Perform shipboard maintenance on rangefinders not requiring the services of an opticalman	2	-	-
.41	Perform shipboard maintenance on optics not requiring the services of an opticalman	2	2	-
.42	Conduct director checks; compute and effect adjustments	2	2	-
.43	Compute corrections to compensate for operator and rangefinder error	2	-	-
.60	Perform tests of director and antenna power drives	1	1	-
.61	Conduct shipboard tests of gyrocontrolled mechanisms	1	1	-
.80	Analyze failures and effect repairs to director and antenna power drives	-	-	C
2.00	Knowledge Factors			
.01	Properties of free and restrained gyros and purpose of damping	3	3	-
.40	Purpose and methods of checking a director to a reference plane	2	2	-
.60	Operating principles of stereo rangefinders; methods used to measure operator and rangefinder errors and methods used to compute corrections (A and B curves)	1	-	-
I.	ADMINISTRATION			
1.00	Practical Factors			
.01	Keep rough logs of periodic tests and maintenance	3	3	-
.40	Make failure reports	2	2	-
.41	Use Navy Stock List of the Ordnance Supply Office	2	2	-
.80	Keep ordnance histories, maintain a Current Ship's Maintenance Project (CSMP) and prepare naval shipyard and tender work requests or job orders	-	-	C
.81	Analyze equipment logs, check-off lists, failure reports, and requisitions for material and casualties	-	-	C

Qualifications for Advancement		Required for Advancement to		
		FTG	FTM	FT
I.	ADMINISTRATION—Continued.			
2.00	Knowledge Factors			
.40	Types of information found in BuWeps and BuShips publications pertaining to weapon control equipment.	2	2	-

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